university of groningen

University Medical Center Groningen

University of Groningen

High-resolution stratigraphy of the northernmost concentric raised bog in Europe

Vorren, Karl-Dag; Wastegard, Stefan; van der Plicht, Johannes; Jensen, Christin; Wastegård, Stefan; Blaauw, Maarten

Published in:
Boreas

DOI:
10.1080/03009480601061152

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Vorren, K-D., Wastegard, S., Van Der Plicht, J., Jensen, C., Wastegård, S., & Blaauw, M. (2007). High-resolution stratigraphy of the northernmost concentric raised bog in Europe: Sellevollmyra, Andoya, northern Norway. Boreas, 36(3), 253-277. DOI: 10.1080/03009480601061152

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 10-02-2018

High-resolution stratigraphy of the northernmost concentric raised bog in Europe: Sellevollmyra, Andøya, northern Norway

KARL-DAG VORREN, MAARTEN BLAAUW, STEFAN WASTEGÅRD, JOHANNES VAN DER PLICHT AND CHRISTIN JENSEN

BOREAS

Vorren, K.-D., Blaauw, M., Wastegård, S., van der Plicht, J. & Jensen, C. 2007 (July): High-resolution stratigraphy of the northernmost concentric raised bog in Europe: Sellevollmyra, Andøya, northern Norway. *Boreas*, Vol. 36, pp. 253–277. Oslo. ISSN 0300-9483.

From the Sellevollmyra bog at Andøya, northern Norway, a 440-cm long peat core covering the last *c.* 7000 calendar years was examined for humification, loss-on-ignition, microfossils, macrofossils and tephra. The age model was based on a Bayesian wiggle-match of 35 ^{14}C dates and two historically anchored tephra layers. Based on changes in lithology and biostratigraphical climate proxies, several climatic changes were identified (periods of the most fundamental changes in italics): *6410–6380*, *6230–6050*, 5730–5640, 5470–5430, *5340–5310*, 5270–5100, *4790–4710*, 4890–4820, 4380–4320, *4220–4120*, *4000–3810*, 3610–3580, 3370–3340 (regionally 2850–2750; in Sellevollmyra a hiatus between 2960–2520), 2330–2220, 1950, 1530–1450, 1150–840, 730? and *c.* 600? cal. yr BP. Most of these climate changes are known from other investigations of different palaeoclimate proxies in northern and middle Europe. Some volcanic eruptions seemingly coincide with vegetation changes recorded in the peat, e.g. about 5760 cal. yr BP; however, the known climatic deterioration at the time of the Hekla-4 tephra layer started some decades before the eruption event.

Karl-Dag Vorren (e-mail: karl-dag.vorren@ib.uit.no) and Christin Jensen, University of Tromsø, Department of Biology, NO-9037 Tromsø, Norway; Maarten Blaauw, Centro de Investigación en Matemáticas, A.P. 402, 36000 Guanajuato, Gto., Mexico; Stefan Wastegård, Department of Physical Geography and Quaternary Geology, Stockholm University, S-10691 Stockholm, Sweden; Johannes van der Plicht, Centre for Isotope Research, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands; received 7th July 2006, accepted 19th September 2006.

The North Atlantic Ocean strongly influences European climate. Through interactions between oceans, ice, landmasses and atmosphere, the climate in this region varies at a range of temporal and spatial scales (e.g. thermohaline circulation, North Atlantic Oscillation; Marshall *et al.* 2001). A spatiotemporal picture of past climate changes in this region could enable a better understanding of their possible causes (e.g. Bond *et al.* 2001). Therefore, precisely dated archives of past climate changes are needed from a diverse array of oceanic and continental European sites. Because raised bogs depend entirely on precipitation for water and nutrients, their deposits form sensitive proxy archives of past climate change (e.g. Mauquoy *et al.* 2004). High-resolution Holocene proxy archives from precisely ^{14}C-dated raised bog peat deposits have recently been constructed from many pan-European sites (e.g. Mauquoy *et al.* 2002a, b; Blaauw *et al.* 2004; Charman *et al.* 2004; ACCROTELM project, http://www2.glos.ac.uk/accrotelm, last accessed 7 Dec. 2006). Although raised bog deposits have been studied from northern Norway, they were analysed and dated at much lower resolutions (e.g. Vorren & Alm 1985; Vorren 2001; Pilcher *et al.* 2005).

The Vesterålen archipelago (Fig. 1) spreads from the Norwegian mainland into the North Atlantic Ocean and is in close proximity to the Gulf Stream and sites of North Atlantic Deep Water Formation (Rahmstorf 2002). These islands form a strategic high-latitude (69°N) oceanic area to add to the spatiotemporal array described above. Sellevollmyra, on the Vesterålen island Andøya, is Europe's northernmost (uneroded) concentric raised bog. Here we report a high-resolution ^{14}C-dated and analysed core from this bog. The core contains a number of known and unknown tephras. These tephras serve to constrain our age model and can be used to compare our archive with those from other European regions.

Tephra (volcanic ash) can be identified to known past volcanic eruptions by their chemical properties (e.g. Larsen 1981; Davies *et al.* 2002). Many volcanic eruptions are fairly well dated, which can lead to the establishment of an independent chronology and precise correlations with other archives such as ice cores and marine cores (however, see Wohlfarth *et al.* 2006 who note several difficulties with establishing tephra chronologies). Numerous tephra layers have been detected in late Quaternary strata in the North Atlantic region, most of them from Iceland. In Scandinavia, so far, more than 25 layers have been reported; some of them are widespread, such as the Vedde Ash (*c.* 12 000 cal. yr BP) and Hekla-4 (*c.* 4260 cal. yr BP), while others have a more patchy distribution and are less valuable for dating and correlation purposes. Veils of volcanic acids drifting around the globe may cause a cooling of climate, most often of a short-lasting

DOI 10.1080/03009480601061152 © 2007 Taylor & Francis

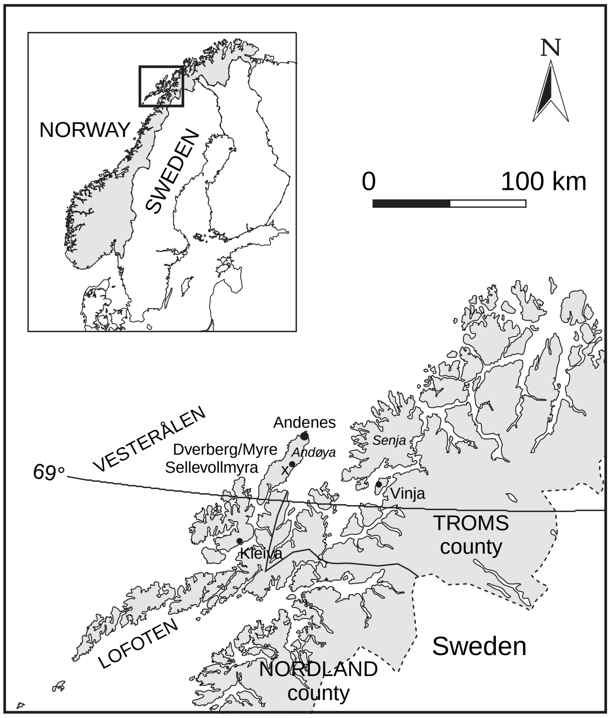

Fig. 1. Location map showing the position of Sellevollmyra (cross) at

and temporary character (Zielinski 2000). Studies of bog stratigraphy may show peculiar vegetation changes associated with tephra layers (e.g. Wells *et al.* 1997); however, this has mostly been reported from areas proximal to volcanoes.

The aims of this study were to: (i) establish a high-resolution chronology based on ^{14}C wiggle-matching and constrained by means of well-known tephra layers; (ii) describe the litho- and biostratigraphic changes in an ombrotrophic mire, which is supposed to reflect a climate strongly influenced by the Atlantic currents and its proximity to the continental shelf; (iii) discuss the indications of climatic change in relation to other investigations related to different types of climate proxies.

The study site

The study concentrated on the raised bog of Sellevollmyra at Andøya, in the Vesterålen archipelago north of Lofoten, Nordland county, Norway. Its geographical position (Fig. 1) is approximately between 69°06′–69°07′N and 15°55′–15°58′E, at an altitude of 10– <20 m a.s.l. The main raised bog element (Fig. 2) covers an area of *c.* 1125 × 1050 m, with its major draining direction approximately towards east–southeast. It is an asymmetric concentric raised bog, with pools, hollows and string hummocks forming the concentric pattern (Fig. 2) and with broad, gently sloping, bog margins. The closest morphologically related type seems to be the ‘kermi-bogs’ of southwestern Finland (cf. Aartolahti 1965) and the concentric bogs of Bergslagen in middle Sweden (Sjörs 1948). Osvald (1925) noted that the centre of the bog was a large, level area without real hollows, and with *Empetrum nigrum* (ssp. *hermaphroditum*)–*Sphagnum fuscum* vegetation alternating with a moister *Empetrum–Ptilidium ciliare* vegetation. Today, the bog centre seems to be wetter than at Osvald’s time, as hollows with *Sphagnum papillosum* and *Sphagnum tenellum* occur. This high plain is also the site of many high ‘bird hummocks’, having reached their size through bird manure and nesting (i.e. by arctic skuas and seagulls). In a transect starting about 50 m from the peat trenches at the southeastern edge towards the coring site at the high plain, peat depths vary between 300 cm and 480 cm, with the ombrogenic peat thickness varying between *c.* 250 cm and 415 cm. Sellevollmyra is situated just north of the section of *Sphagnum imbricatum* bogs that occurs north of Lofoten and the southern part of the Vesterålen archipelago.

The GPS position of the coring site was 33W 0537022 7666063 (referring to the M711 grid) and the height a.s.l. was between 11.8 m and 13.3 m. The vegetation at the coring site was dominated by *Andromeda polifolia*, *Trichophorum cespitosum*, *Gymnocolea inflata* and *Sphagnum tenellum*. This lawn was limited to the north by a high bird hummock, to the east and west by vegetation dominated by *Empetrum nigrum* ssp. *hermaphroditum*, and towards the south by a hollow dominated by *Sphagnum papillosum*.

The climate of the Sellevollmyra area is probably intermediate between the meteorological observation stations Andøya and Kleiva (cf. Førland 1993; Aune 1993). Annual precipitation is estimated to be about 1200 mm, with maximum mean precipitation in the autumn (October, 150–200 mm) and minimum mean in the spring (April–May, about 60 mm in each month). The annual mean temperature is about 4°C, with the July mean temperature being *c.* 11.5°C and January–February mean temperatures *c.* –2°C.

The subterrain of Sellevollmyra is formed by Lateglacial and Holocene raised beaches. The Tapes shoreline (8300–7400 cal. yr BP) was formed by a transgression up to 9–10 or 7.5 m above present sea level (Møller 1986; Vorren & Moe 1986). This shoreline dams the bog towards the southeast but is overgrown by peat towards the east.

To document the regional occurrence of the climatic deterioration about 2850–2750 cal. yr BP, a peat series from Vinja was chosen. Vinja is located on an island *c.* 40 km east of Sellevollmyra (Fig. 1). The Vinja site is an eccentric, ombrotrophic bog sloping towards the west.

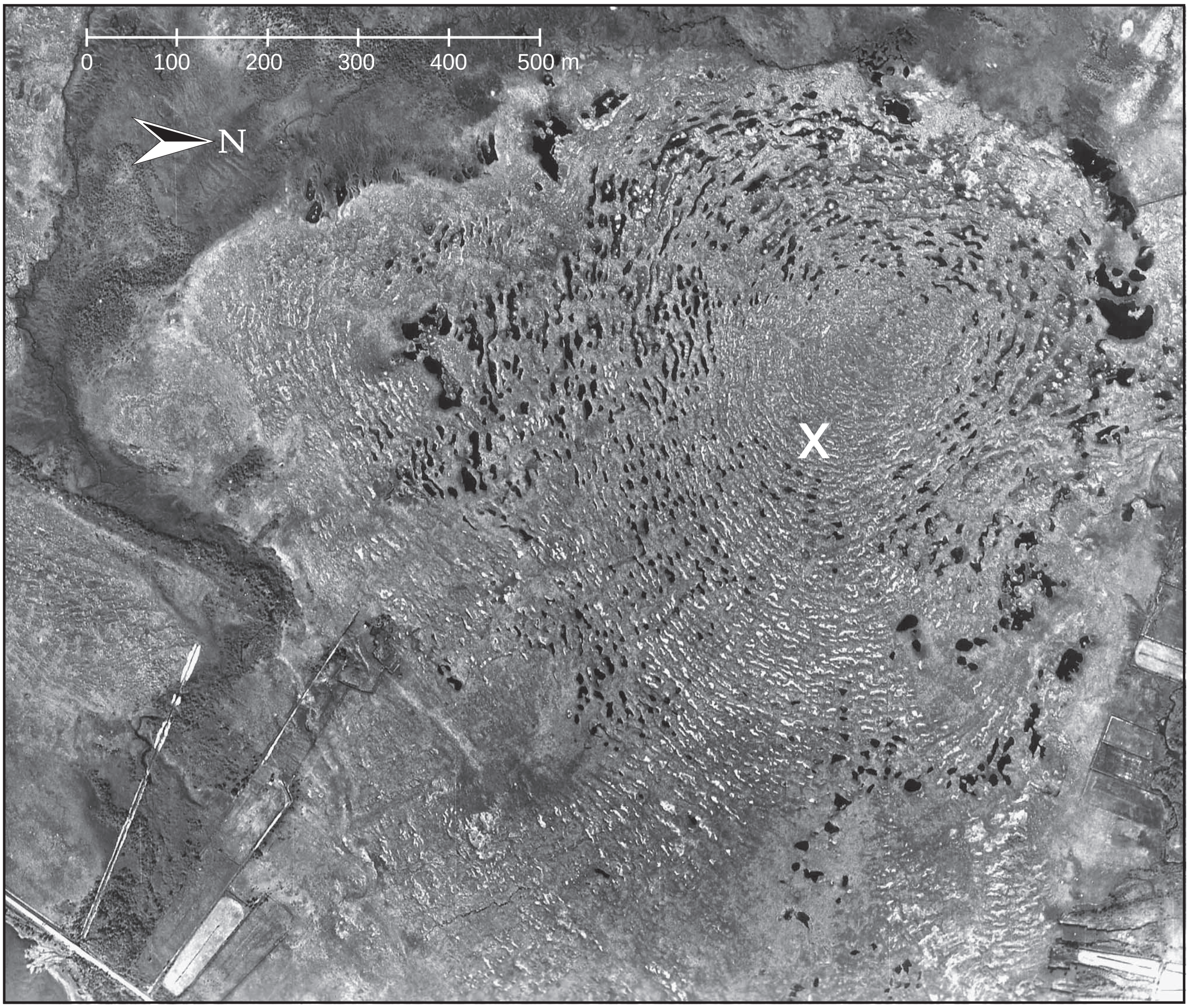

Fig. 2. The Sellevollmyra raised bog element, vertical photo from 1954, by Fjellanger-Widerøe Aerial Photo. The cross marks the coring site.

Materials and methods

The core was retrieved on 29th September 2000, at the eastern margin of the high plain of Sellevollmyra (Fig. 2). Three plastic tubes with an inner diameter of 10 cm were successively hammered down by means of a sledge and an adapted aluminium disc on the top of the tubes, and dug out with spades and bores. The total length of the sequence was 440 cm, leaving the lowermost strata down to *c.* 480 cm unsampled but including the transition interval between minerogenic and ombrogenic peat. In the laboratory, the tubes were split longitudinally by a saw and the cores rinsed carefully. The lithology was described according to von Post's (von Post & Granlund 1926) humification degrees, together with an ocular determination of the main macrofossil assemblage in the different layers. Thereafter the core was cut into 1-cm thick peat slices, which were stored in air-tight plastic bags and plastic boxes.

Humification of the peat was measured for every second centimetre by means of Overbeck's colorimetric method, modified by Bahnson (Aaby 1986). The peat was dried at 105°C for 24 h and pulverized. A subsample of 0.1 g was boiled in 50 ml 0.5% NaOH for 30 min and then diluted with 50 ml distilled water, filtered and diluted again with 100 ml distilled water. Using a Shimadzu UV-1201 spectrophotometer at 540 nm, the measured absorbance for each sample was related to distilled water (=0). For the Vinja series a reference sample with 0.2 g dissolved humic acid was used as a reference (=100%) and the values were calculated as percentages of the reference sample.

Loss-on-ignition (LOI) was investigated by drying 3-ml samples at 105°C for 16–24 h and combusting them at 600°C for *c.* 2 h.

Tephra was analysed using methods outlined by Pilcher *et al.* (1995); 5–10-cm contiguous peat slices were combusted at 550°C for 4 h, washed in 10% HCl and mounted for microscopy in Canada Balsam. For those samples from which tephra shards were detected, the equivalent sediment was resampled using 1- or 2-cm slices. Tephra concentrations were estimated with the aid of *Lycopodium* tablets. Some tephra samples were prepared for electron microprobe analysis using Wavelength Dispersive Spectrometry (WDS). These samples were acid digested following the procedure outlined by Dugmore (1989), and analysed with a Cameca SX100 electron microprobe equipped with five vertical WD Spectrometers. Ten major elements were measured with a counting time of 10 seconds. An accelerating voltage of 20 kV and beam strength of 10 nA, determined by a Faraday cup, were used, with a rastered beam over an area of 10×10 μm to reduce instability of the glass and subsequent sodium loss. For some small shards, spot analyses were performed (*c.* 3–5 μm) rather than raster analyses. Calibration was undertaken using a combination of standards of pure metals, simple silicate minerals and synthetic oxides, including andradite. These were used regularly between analyses to correct for any drift in the readings. A PAP correction was applied for the effects of X-ray absorption (Pouchou & Pichoir 1991). All elements are expressed as weight%. So far only four horizons have been analysed. Three of these have produced results that allow correlations with other tephra horizons from northwest Europe.

At intervals of 2, 4 and 8 cm, 1- or 2-ml samples were heated in 5% KOH and washed in distilled water through a sieve with a 0.2-mm mesh size to concentrate the coarser macrofossil remains, after which the material was examined under two cover glasses, 22×32 mm. From 130–100 cm depth, at every centimetre, 5-ml peat samples were heated in 5% KOH, washed in distilled water and studied in Petri dishes. For determination of vascular plants, Beijerinck (1947), Nilsson (1961), Lid & Lid (1994) and a local seed collection were used, and for the mosses Nyholm (1956–69). The group Sphagna Acutifolia is mainly composed of *Sphagnum rubellum* and *Sphagnum fuscum.* The frequency characters 'none' and 1–3 are set by a subjective estimation.

Because of extremely low pollen and spore concentrations, 2 ml peat was sampled from every 4-cm level for microfossil analysis. The samples were treated by the common KOH and acetolysis method (Fægri & Iversen 1989) and two tablets with *Lycopodium clavatum*, containing $12\,100 \pm 200$ spores each, were added. Some samples rich in ligneous remains were also prepared using oxidation and a treatment with a composite liquid to prevent bleaching and swelling (Institute of Botany, University of Innsbruck, unpublished method). Prepared samples were stained with basic fuchsine. The aim was to count >400 terrestrial pollen. The pollen and spore taxonomy and nomenclature in general follow the key in Fægri & Iversen (1989), with the exception for some taxa, such as Polypodiaceae, here 'Pteropsida, monolete' (Bennett 1994). For distinction of *Betula* tree pollen from *Betula nana*, the characteristics of Eneroth (1951) were employed. [It should be emphasized that pollen size varies according to the acid/base status of the peat. The lowermost (440–420-cm) pollen samples from basic peat include a large proportion of small pollen, determined as *Betula nana*-type. However, only tree birch macrofossils occur here.]

The records of Rhizopoda and Rotifera were based on the amount of material prepared for pollen analysis under two cover glasses, 22×32 mm. Only the Rhizopoda *Assulina muscorum*, *Assulina seminulum* and *Amphitrema flavum* (cf. Nilsson 1961; Tolonen 1966) and the rotifer *Callidina* (cf. *angusticollis*) (van Geel 1978) seemed to be able to resist the acetolysis process.

The proxy diagrams were produced using TILIA 2.0.b4 (Grimm 1993) and TGView 2.0.2 (Grimm 2004). Zonation of the diagrams comprises two sets of pollen and spore taxa: (i) the mire vegetation (mire herbs, Ericales, *Calluna* and *Betula nana*) and (ii) the terrestrial vegetation (trees, shrubs including *Betula nana*, terrestrial herbs, in two versions, with and without Pteropsida monolete, *Gymnocarpium* type). The zonation was carried out using both CONISS (Grimm 1987, 2004) and 'binary splitting by information content' in PSIMPOLL 4.25 (Bennett 1996, 2005). The pollen data were square-root transformed prior to the analyses.

For the age model, 35 samples, mainly moss stems (seeds in some cases; mosses were mostly Sphagna), were carefully cleaned for hyphae, vascular root compounds and other fragments. After AAA pretreatment (Mook & Streurman 1983), the samples were ^{14}C dated. Most samples were dated using AMS, while the lowest sample was dated conventionally. An age model for the entire sequence of dates was constructed using Bpeat (Blaauw & Christen 2005) with IntCal04 (Reimer *et al.* 2004). Bpeat uses ecological information to constrain the piece-wise linear age model. To account for abrupt accumulation rate changes, the core was divided into multiple sections. The most probable accumulation rates are those of fresh bogs, which accumulate at 20 ± 10 yr/cm. A weak dependency of accumulation rates exists between sections (Gamma distribution with Epsilon set at 5; Blaauw *et al.* in press). If a hiatus is present, its length is short (parameters HiatusA 0.05, HiatusB 0.005). Prior outlier probabilities of ^{14}C dates are 5% (except the lowermost date; see below) and the core surface could not post-date AD 2000 (−50 cal. yr BP, where cal. yr BP = calendar years before AD 1950), the year of sampling. The lowermost date was taken from *Phragmites*–Cyperaceae peat, which is likely to have had a different accumulation rate than a raised bog peat. Therefore, to obtain an accumulation rate change between the lowermost and the other dates (instead of assuming a constant accumulation rate and treating the lowermost date as an outlier), a 0% prior outlier

Table 1. ^{14}C dates in the Sellevollmyra peat sequence. ^{14}C ages BP with 1 SD confidence intervals. ND = not determined.

Lab. no.	Depth (cm)	Dated material	^{14}C age	$\partial^{13}C$ ‰
TUa-3756	12–13	*Sphagnum rubellum* stems, 1 *Empetrum* seed	845±40	−27.0
TUa-3757	34–35	*S. magellanicum* stems, 7 *Emp.*, 1 *Rubus ch.* seeds	1185±45	−25.5
TUa-3758	55–56	*S. rubellum* stems	1645±45	−28.5
TUa-3759	77–78	*S. rubellum* stems	2035±45	−27.1
TUa-3760	90–91	*S. rubellum* stems	2250±45	−28.6
GrA-23092	100–101	*Sphagnum* stems	2540±45	ND
TUa-3761	103–104	*S. rubellum* and *S. balticum* stems	2440±45	−26.0
GrA-23093	107–108	*Sphagnum* stems	2750±50	ND
GrA-23098	111–112	*Sphagnum* stems	2975±40	−27.5
GrA-23089	113–114	*Sphagnum* stems	2865±40	ND
GrA-23088	115–116	*Sphagnum* stems	2870±40	−28.5
GrA-23097	117–118	*Sphagnum* stems	2985±40	−28.1
GrA-23095	119–120	*Sphagnum* stems	2885±40	−28.5
GrA-23094	120–121	*Sphagnum* stems	2950±40	−28.8
GrA-23087	121–122	*Sphagnum* stems	2905±40	−28.9
GrA-23090	122–123	*Sphagnum* stems	2985±45	−28.4
TUa-3762	123–124	*S. fuscum* stems, 1 *Empetrum* seed	2905±45	−27.7
TUa-3763	146–147	*S. rubellum* and *S. lindbergii* stems	3285±50	−29.1
TUa-3764	158–159	*S. rubellum* and *S. lindbergii* stems	3320±45	−26.7
TUa-3765	177–178	*S. rubellum* and Sphagna Cuspidata stems	3715±45	−27.1
TUa-3766	187–188	*Drepanocladus fluitans* stems	3635±45	−23.7
TUa-3767	205–206	*S. rubellum* and *Drepanocladus fluitans* stems	3800±45	−29.0
TUa-3172	218–219	*Hylocomium splendens* and *Empetrum* seeds	3950±70	−26.2
TUa-3768	235–236	Sphagna Acutifolia and *Drepanocladus fluitans* stems	3690±50	−25.7
TUa-3769	247–248	*S. capillaceum (nemoreum)* stems, *Dicranum* leaves	3835±50	−27.5
TUa-3770	269–270	Sphagna Acutifolia stems, *Empetrum* seeds	4075±50	−27.7
TUa-3771	285–286	Sphagna Acutifolia stems	4440±50	−27.9
TUa-3772	303–304	Sphagna Acutifolia stems	4310±50	−26.6
TUa-3773	320–321	Sphagna Acutifolia stems	4715±50	−27.4
TUa-3774	342–343	Sphagna Acutifolia stems	4670±50	−28.1
TUa-3775	362–363	Sphagna Acutifolia stems	4880±50	−27.6
TUa-3777	384–385	Sphagna Acutifolia stems	5130±50	−28.5
TUa-3173	405–406	Sphagna Acutifolia stems	5110±50	−28.8
T-18301	434–435	*Betula* root, *Phragmites* and *Carex* stems/stolons	5865±50	−29.1

probability was given to this date. The age model was further constrained through anchoring the 16.5-cm depth at 846±1 cal. yr BP and the 14.5 cm depth at 792±1 cal. yr BP, because at these depths the historic tephras Hekla-1 (AD 1104) and Hekla-1158 (AD 1158) were identified (the former was identified geochemically and the latter was inferred to be most likely Hekla-1158). Under the above assumptions, through Monte Carlo Markov Chain iterations >720 million possible age models were used to find the best age models and confidence intervals (Blaauw & Christen 2005). Calendar ages outside the ^{14}C-dated section (440–435 cm and 13–0 cm) were estimated through extrapolation; these ages should be interpreted with caution and we refrain from giving estimates to depths between 12 cm and the core surface.

Results

Chronostratigraphy

The 35 ^{14}C dates (Table 1) were run repeatedly through Bpeat (Blaauw & Christen 2005) to ensure reproducible results. Without core division or with two to three sections, no successful fits could be obtained (low fit F; Blaauw & Christen 2005) while a good fit (F 95.15%) was obtained using four sections (Fig. 3). In the text, calendar ages are rounded to the nearest decade and should be interpreted as approximate. Some outlying dates were present between 5000 and 4500 cal. yr BP. The peat deposition time was *c.* 30 yr/cm at the bottom of the sequence (*Phragmites*–Cyperaceae peat). A change towards a much faster deposition time (*c.* 7 yr/cm) was inferred around the 410-cm depth (*c.* 5930 cal. yr BP), which coincided approximately with the start of *Sphagnum* peat. Around 271 cm (*c.* 4990 cal. yr BP) and 107 cm, the deposition time slowed to *c.* 12 and *c.* 19 yr/cm, respectively. The latter change in deposition time was accompanied by a hiatus lasting from *c.* 2960 to 2520 cal. yr BP.

Lithostratigraphy

Humification. – The generally low humification rates left only a few distinct layers and clear 'recurrence surfaces'. The transition from a Cyperaceae peat with *Phragmites* and *Betula pubescens* s.l. remains to a *Sphagnum*–Ericales-dominated peat at about 420 cm below the surface was most prominent. The simplified

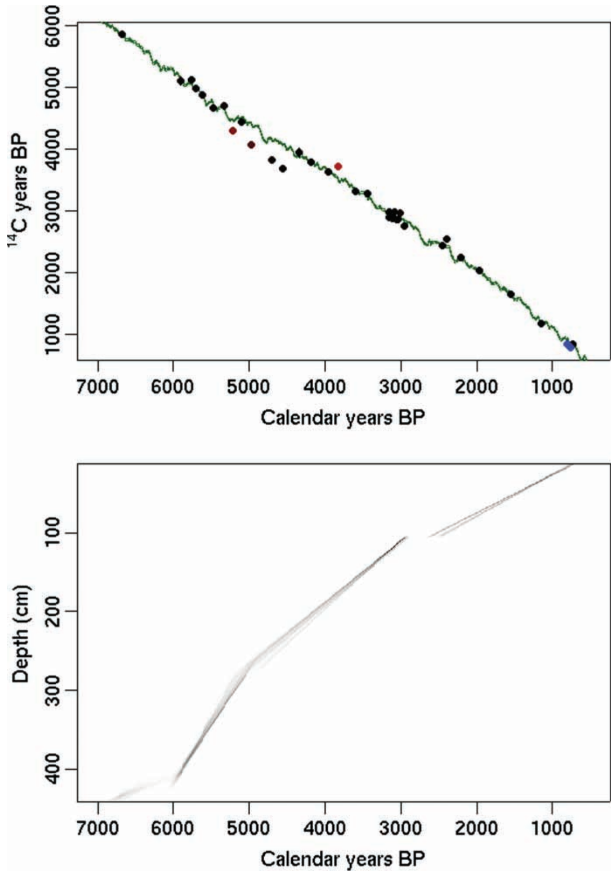

Fig. 3. Wiggle-matching of 34 AMS ^{14}C dates (black to red dots), one conventional date and two historically anchored tephra layers (blue) of the Sellevollmyra peat sequence. See text. The upper panel shows the fit of the dates to the IntCal04 calibration curve (Reimer *et al.* 2004); the lower panel shows the age model with grey scales indicating the chronological uncertainty (Blaauw & Christen 2005). Red dates were identified as outliers (Blaauw & Christen 2005).

stratigraphy is presented in Fig. 4 and Table 2. Between 430 cm and 0 cm depth, the colorimetric humification oscillated between 0.2 and 0.6 (Fig. 4, Table 3). The von Post's humification degrees oscillated between H3 and H6, except the strata below 410 cm, where values up to H9 were noted (Table 2). The oscillation from higher to lower humification (wet shift) is often considered to be climatically conditioned, especially when accompanied by changes in vegetation composition. In principle, wet shifts correspond with the recurrence surfaces (RY) of Granlund (1932). Twenty-eight such humification changes, from >0.4 to <0.3 absorption units, could be noted in the humification curve of Sellevollmyra. In 18 cases the absorption units declined below 0.25. No obvious temporal regularity between the humification changes could be seen. They occurred with irregular intervals of 50–420 years (920 years if the late Subboreal interval, having a 440-year hiatus, is included). Five out of 27 calculated shifts followed after a period of 50 years, three after 110–130 years, six after 140–160 years, five after 190–220 years and three after 240 years. The most marked humification shifts (<0.25 absorption unit) were most frequent in the periods 5320–4840, 4320–4170 and 3820–3420 cal. yr BP. On the other hand, humification peaks may indicate periods with a warmer climate. The highest peaks have been dated at 5590–5480 and 5480–5330 cal. yr BP. Other peaks occurred between, for example, 3200–3150, 2060–1980, 1260–1180 and 840–750 cal. yr BP. To compare the humification shifts at Sellevollmyra, not relative to a humic acid standard, and to show the regional occurrence of a marked wet shift about 2750 cal. yr BP, we used the Vinja sequence from a neighbouring island (Fig. 1). This peat sequence has been pollen analysed and dated by means of four conventional ^{14}C dates and examined for humification. The pollen diagram from Vinja (Vorren & Alm 1985) shows a rather synchronous rise of the Ericales, *Rubus chamaemorus* and *Sphagnum* curves about 6000–6400 cal. yr BP (5300 BP), under a transition to low-humified peat. There are several wet shifts (Fig. 5), of which the one interpolated to about 2750 cal. yr BP should be mentioned. The humification percentages vary clearly between highs and lows.

Loss-on-ignition. – The LOI values (Fig. 4) are shown as running means for every vertical centimetre. The values oscillate mainly about 98% but occasionally around 97%. In the uppermost part of the sequence and towards the present time there are a couple of depressions, which are probably related to human activity. The fact that the village of Dverberg became a municipality centre during the late Medieval period seems to be reflected in the LOI decline in the uppermost 10 cm. The minor decreases in LOI about 5310 and 4330 cal. yr BP should be noted.

Tephra. – The main results of the tephra investigation in the Sellevollmyra sequence are displayed in Table 4. In total, 11 layers were distinguished, of which four have been analysed so far. Horizons of colourless to brown tephra were found, with concentrations ranging from *c.* 10 to more than 12 000 shards/cm^3 wet peat (Table 4). Geochemical data were obtained from four tephra layers (SEL-2, SEL-3, SEL-6 and SEL-10; Table 4, Fig. 6). Identification of the other layers were either unsuccessful or are awaiting identification. Many shards were burnt through by the electron beam because of the small shard sizes and high vesicularity, and all analyses >93% were accepted, in contrast to the recommendations by Hunt & Hill (1993), who argued that all analyses below 95% should be rejected. Analyses of the SEL-2, SEL-3, SEL-6 and SEL-10 layers are presented as a biplot of CaO vs. FeO_{tot} in Fig. 6 and Table 5. The uppermost analysed tephra layer, SEL-2, had a peak concentration at 16–17 cm of 1810 shards/cm^3. Geochemical analyses suggest a correlation with the Hekla-1 tephra, which

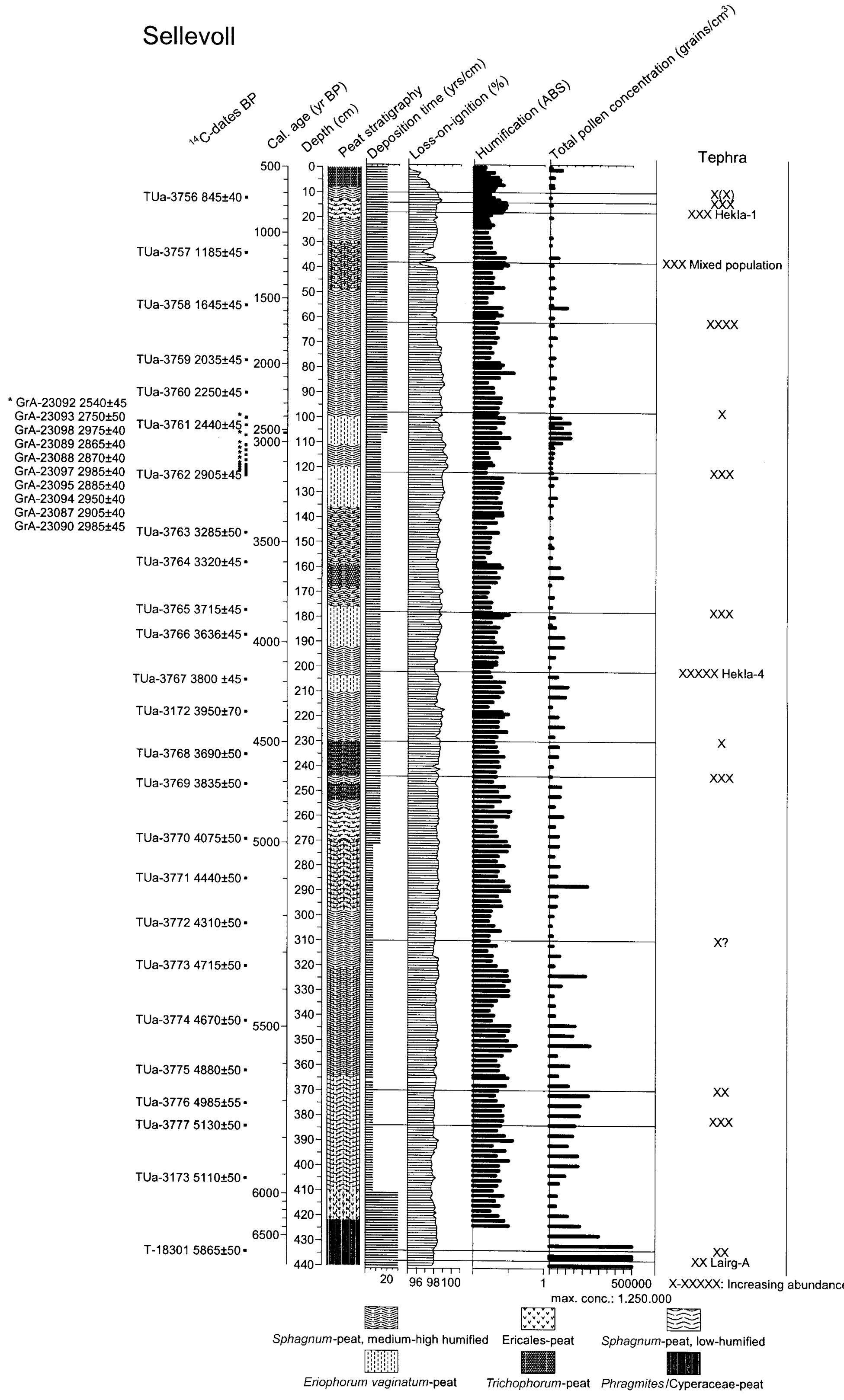

Fig. 4. Chrono- and lithostratigraphy of the Sellevollmyra peat sequence, with peat classification, sedimentation rates, pollen concentration, humification units, LOI and

Table 2. Description of the peat layers in the Sellevollmyra sequence. Hum = humification degrees on von Post scale by ocular assessment (von Post & Granlund 1926). NS = not sampled.

Depth (cm)	Stratigraphy	Hum
0–8	*Trichophorum cespitosum–Sphagnum rubellum*	5
8–13	*Sphagnum*	3
13–21	*Sphagnum*–Ericales	5
21–30	*Sphagnum*	3–4
30–99	*Sphagnum*–Ericales–*Eriophorum vaginatum*	3–5
99–111	Ericales–*Eriophorum vaginatum–Sphagnum*	5
111–120	*Sphagnum*–Ericales	3
120–136	*Eriophorum vaginatum–Sphagnum*	5
136–158	*Sphagnum*–Ericales	4
158–168	*Eriophorum vaginatum–Sphagnum*	5
168–176	*Sphagnum*–Ericales–*Eriophorum vaginatum*	4–5
176–192	*Eriophorum vaginatum–Sphagnum*	5–6
192–203	*Sphagnum*	3–4
203–210	*Eriophorum vaginatum–Sphagnum*	5
210–230	*Sphagnum*	4–5
230–244	*Sphagnum–Trichophorum cespitosum*	4–5
244–247	*Sphagnum*	4
247–254	*Sphagnum–Trichophorum cespitosum–Eriophorum vaginatum*	4–5
254–257	*Sphagnum*	3–4
257–270	*Sphagnum*–Ericales	3–4
270–300	*Sphagnum–Eriophorum vaginatum–Ericales*	4–5
300–321	*Sphagnum*	3–4
321–364	*Sphagnum*–Ericales–*Eriophorum vaginatum*	4–5
364–410	*Eriophorum vaginatum–Sphagnum*	5–6
410–422	*Eriophorum vaginatum*–Ericales	6–7
422–440	*Phragmites–Carex* with *Betula* roots	7–9
440–480	*Phragmites–Carex* peat with increasing dominance of tree remnants towards the mineral ground	NS
480	Gravel and sand	NS

erupted AD 1104. This eruption was the largest of Hekla in historic times (Thorarinsson 1967) and the tephra is distinguished from the slightly younger Hekla-1158 tephra, described earlier from the Lofoten islands by Pilcher *et al.* (2005). The SEL-3 tephra, with a peak concentration at 36–38 cm, had a mixed population and it was not possible to correlate it with any known tephra layer. Some shards had affinity with the AD 860 tephra, described from the British Isles, Iceland and Germany (e.g. Wastegård *et al.* 2003). SEL-4 and SEL-5 have not been analysed. The Bpeat ages for these layers indicated a possible correlation with the Hekla-3 (*c.* 3000 cal. yr BP; van den Bogaard *et al.* 2002) and Kebister (*c.* 3750 cal. yr BP; Gunnarson *et al.* 2003) tephras, but this needs to be confirmed with geochemical analyses. SEL-6 had the highest concentration of all tephra layers at Sellevollmyra. Geochemical analyses indicated a correlation with the first erupted magma of the Hekla-4 eruption (e.g. FeO_{tot} around 1.8–1.9% and CaO contents of *c.* 1.3%; Fig. 6), except for one shard representing a later phase of the eruption. A correlation with Hekla-4 was also supported by the Bpeat age (Table 6). SEL-7, SEL-8 and SEL-9 were not analysed. The composition of SEL-10 was almost identical to SEL-6 but was *c.* 2600 years older. It is known that the Lairg-A tephra (*c.* 6900 cal. yr BP), previously found in the British Isles, Sweden and the Lofoten islands, is geochemically inseparable from Hekla-4 tephra. This is further complicated by the fact that two distinct tephra layers with identical main element geochemistry were found on the Borge bog in Lofoten, separated by only 500 years (Pilcher *et al.* 2005). These were believed to represent two different eruptions of Hekla, probably Lairg-A and Hekla-5 (*c.* 7300 cal. yr BP). This interpretation is supported by a recent study from western Ireland (Chambers *et al.* 2004), where two layers, interpreted to represent Lairg-A and Hekla-5, were identified. As only one layer with this chemical composition was found in the Sellevollmyra peat sequence, we cannot be certain which eruption SEL-10 represents. However, the age derived from Bpeat suggests that SEL-10 can be correlated with the Lairg-A tephra, although our study indicates a slightly younger age than previous estimates (Table 4).

Biostratigraphy, results and interpretation

The biostratigraphical interpretation is based on separate relative and absolute pollen and spore diagrams and diagrams of other fossils. The local mire development is considered first (Figs 7, 9, Table 7), then the regional vegetation (Figs 4, 8, 9).

Local mire development. – The numerical zonation in the combined relative pollen diagram and presence–absence diagram for macrofossils and Rhizopoda and Rotifera (Fig. 7) is based on pollen of dwarf shrubs, Cyperaceae and mire herbs and *Sphagnum* spores. Both (PSIMPOLL and CONISS) showed very similar zonations, except for additional CONISS limits about 5200, 4790, 3950 and 2300 cal. yr BP, which are included in the overview (Fig. 10). Ten pollen assemblage zones (PAZ) were distinguished (Fig. 7) but the main changes occurred in PAZ M1 and M2 (>6820–5930 cal. yr BP) and M5 (4790–4180 cal. yr BP). The transition from minerotrophic to ombrotrophic mire vegetation occurred in the interval at 426–410 cm depth (PAZ M2, 6410–5930 cal. yr BP), where the Ericales rise indicates an acidification most probably caused by a period with a climatically conditioned low water table. After the Ericales expansion there is a rise of Sphagna Acutifolia, probably dominated by *Sphagnum fuscum*. The period with *Aulacomnium palustre* as a characteristic macrofossil at about 5730–5640 cal. yr BP indicates a slight rise of the water table or the formation of draining soaks, as the species is dependent on at least weakly minerotrophic conditions (e.g. Vorren *et al.* 1999; its main occurrence is in the vegetation alliance Caricion canescenti-fuscae). After that, the presence of the moss *Hylocomium splendens* indicates the presence of high hummock vegetation until about 4730 cal. yr BP.

Table 3. Wet shifts in the Sellevollmyra sequence. Those levels marked with an asterisk are considered 'marked wet shifts' with humification units below 0.25. 'Dry shifts' in the two columns to the right.

<0.3 absorption units		>0.4 absorption units	
Interval (cm)	Age range (cal. yr BP)	Interval (cm)	Age range (cal. yr BP)
5–0*	?–?	9–5	?–?
13–9*	730–?	19–14	840–750
35–19*	1150–840	41–37	1260–1180
45–41	1340–1260	50–48	1430–1390
55–51*	1530–1450	83–79	2060–1980
61–60	1640–1620	103–100	2440–2380
77–71	1950–1830	109–107	2970–? (hiatus)
91–85	2220–2100	127–123	3200–3150
123–113	3150–3020	181–179	3870–3850
141–139	3370–3350	195–191	4050–4000
145–143*	3420–3400	211–205	4240–4170
159–147*	3580–3450	221–218	4370–4330
177–167*	3820–3700	227–225	4440–4420
189–187	3970–3950	238–236	4580–4560
205–199*	4170–4100	249–247	4720–4690
217–213*	4320–4270	253–251	4770–4740
221–219	4370–4340	261–258	4870–4830
249–247	4710–4640	275–269	5020–4970
259–257*	4840–4820	333–321	5480–5330
263–261*	4890–4870	359–343	5590–5480
305–297*	5220–5170	369–363	5660–5620
311–307*	5270–5240	391–377	5810–5710
319–313*	5320–5280	399–397	5860–5850
343–333*	5480–5410	425–423	6380–6320
375–373	5700–5680		
393–391	5820–5810		
411–409	5960–5930		
419–417*	6200–6140		

The start of continuous *Amphitrema flavum* (*c.* 5060 cal. yr BP) and *Assulina seminulum* (*c.* 4730 cal. yr BP) curves may indicate parallel formation of hollow vegetation in the close surroundings. Even if the indicator value of testate amoebae remnant after acetolysis is questionable (Hendon & Charman 1997), we think that this presence–absence survey (Fig. 7) correlates well with other parameters (e.g. the *Assulina seminulum* curve vs. the Ericales pollen curve). The development towards wet bog vegetation (cf. the Cyperaceae curve) accelerated after *c.* 4180 cal. yr BP (possibly coeval with climate changes in other regions; cf. Drysdale *et al.* 2006), with increasing participation of *Calluna vulgaris* in periodic shifts between dry and wet conditions. It should be emphasized that although *Eriophorum vaginatum* is a 'ubiquitous and omnipresent' species (Økland 1989, 1990) at Sellevollmyra, it was already present and partly dominant from a depth of 422 cm (Table 2) without contributing much to the Cyperaceae pollen taxon. Our opinion is that the hollow species *Trichophorum cespitosum* and the pool margin species *Eriophorum angustifolium* together with *Carex rariflora*, growing in low hummocks as well as wet carpets in the hollows, are responsible for the increase in Cyperaceae about 4000 cal. yr BP. The *Calluna* peaks are part of a succession pattern between hollows (Cyperaceae), low hummocks (*Calluna*) and high hummocks (Ericales/*Empetrum*) that was probably climatically induced. The intervals between the *Calluna* peaks vary between 320 and 620 years (three cases) (and 1320 if we include the hiatus interval 2960–2520 cal. yr BP). The most fundamental, probably climatically determined, changes in the local development of the mire/bog occur at the transitions PAZ M2/3 (5930 cal. yr BP) (strong expansion of 'dry' oligotrophic vegetation), PAZ M4/5 (4730 cal. yr BP) and PAZ M5/6 (4180 cal. yr BP) (accelerated expansion of hollows and pools: more humid and probably also colder winters).

Macrofossils in the core interval 130–100 cm. – Based on an expected 'recurrence surface' (RY, or shift from dry to moist peat-forming vegetation) in the peat about 2800–2700 cal. yr BP (cf. regional RY; Nilssen & Vorren 1991; Vorren 2001), special attention was given to the 130–100-cm interval. A dense series of 12 AMS dates from this interval was sampled to provide a secure wiggle-matched age model for this section. Macrofossils (Table 7) indicate mainly different hummock levels: a high hummock with Ericales (excl. *Calluna*) vegetation between 130 and 123 cm; a low hummock dominated by *Sphagnum fuscum* between 123 and 111 cm; a 1-cm thick layer with hollow taxa (*Sphagnum magellanicum* and *Sphagnum tenellum*) at

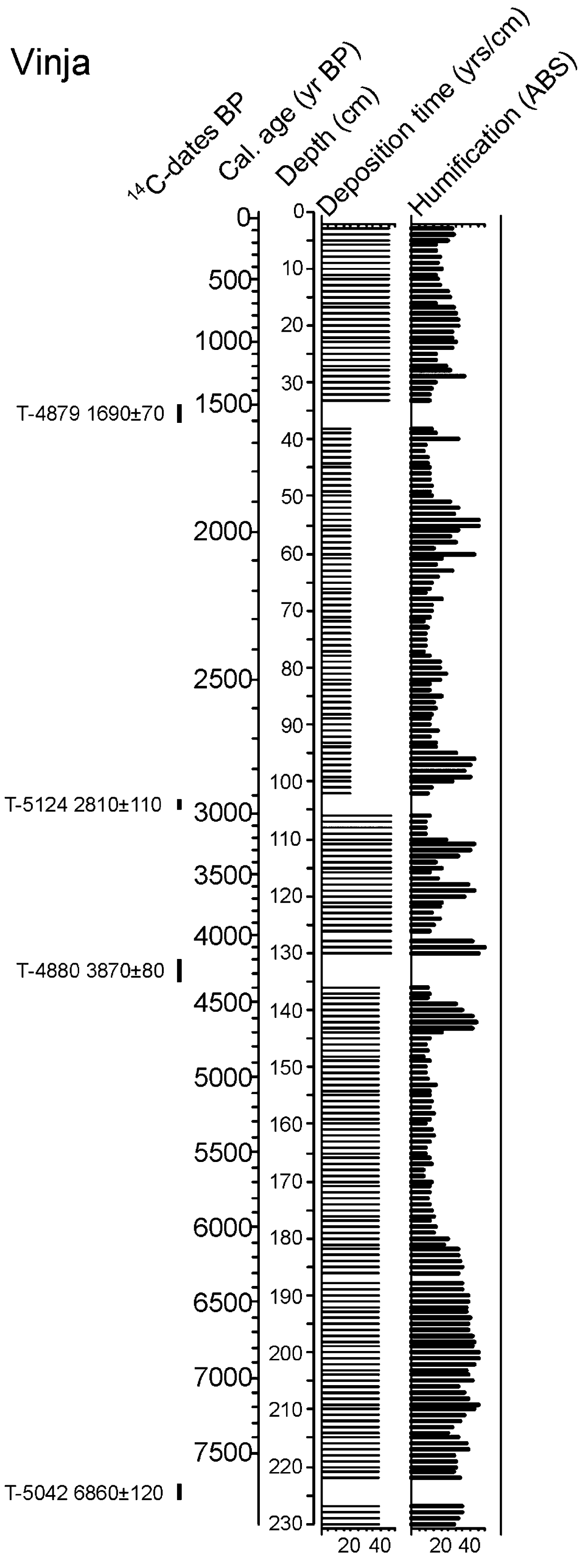

Fig. 5. Humification diagram from Vinja, an island *c.* 40 km east of Sellevollmyra. Humification values are given as percentage transparency of a standard humic acid solution. The age scale is a linear inter- and extrapolation scale based on four ^{14}C dates calibrated using IntCal04 (Reimer *et al.* 2004).

111–110 cm; and hummock vegetation again between 110 and 100 cm. It was suspected that this wet shift between 110 and 109 cm might conceal a hiatus (i.e. between 2975 ± 40 ^{14}C BP and 2 cm below a date of 2750 ± 50 ^{14}C BP). However, according to the age–depth model (Fig. 3) the possible hiatus is placed between 107 and 108 cm and estimated to be of *c.* 430-year duration (95% confidence range 278–483 calendar years). The increased pollen accumulation rate (PAR) about this interval may indicate that the estimated hiatus length is too large.

Terrestrial and regional vegetation (trees, terrestrial herbs and ferns). – The zone divisions (Fig. 8) are mainly based on CONISS (Grimm 2004), which seemed to produce the 'best fit' with the small variations in the pollen curves of the terrestrial plants. However, the main divisions (PAZ T1–4) have been assessed subjectively. In a zonation procedure without ferns, PSIMPOLL indicated main divisions at 10.5 cm (650? cal. yr BP), 186.5 cm (3950 cal. yr BP), 294.5 cm (5160 cal. yr BP) and 430.5 cm (6560 cal. yr BP), which are included in the overview (Fig. 10) as PAZ limits. Four main PAZ have been distinguished: PAZ T1–4. PAZ T1 (>6820–6380 cal. yr BP) reflects the local development of the mire, i.e. the transition to ombrotrophic stages via a succession phase characterized by *Betula* cf. *nana*. PAZ T1 and T2 (6380–4770 cal. yr BP) constitute a period with shifts between continental and oceanic climate types, but generally with warmer summers than at present, indicated by the oscillating pine curve and the generally high *Alnus* and fern curves. PAZ T3 (4770–4470 cal. yr BP) represents a regional climatic change. The low fern curve in subzone T3a (4770–4470 cal. yr BP) may be interpreted as a signal of either frosts while the ground is bare in autumn and winter or late spring frosts damaging young ferns. The low pine curve, the alder minimum and the birch maximum favour the latter hypothesis, a climate shift towards cool and moist conditions with short, cool and rainy summers and long snow-rich winters. The changes at the limit T3–4 (3340 cal. yr BP) are the result of the start of agricultural activity in the surroundings of Sellevollmyra.

PAR in mire vegetation and terrestrial, regional vegetation without ferns. – PSIMPOLL suggests four zones for the mire pollen and spore taxa: PARZ M1, 440–405.5 cm, >6820–5910 cal. yr BP, with a depression in all curves; PARZ M2, 405.5–322 cm, 5910–5340 cal. yr BP, with a rather steady and high rate for

Table 4. The tephra layers recorded in the Sellevollmyra sequence. The dates have 95% confidence intervals for the Bpeat calendar age estimates of core levels containing tephra. Estimates marked with ~are approximate as the depths of the peak concentrations of those tephra layers were not determined precisely. Concentrations are given as shards/cm^3 wet peat. Question marks indicate possible (but uncertain) identities. Geochemically identified tephra layers are marked with bold text. Known ages (in cal. yr BP) refer to historically dated tephras [Hekla-1 (AD 1104), Hekla-1158 and Öræfajokull-1362] and published ages for prehistoric tephras (e.g. Pilcher *et al.* 1995; van den Bogaard *et al.* 2002; Gunnarson *et al.* 2003). Concentration refers to peak concentrations, rounded to the nearest 10 (shards/cm^3 wet peat; ND = not determined). Bpeat ages give the 95% ranges (cal. yr BP) with the maximum a posteriori ('best age estimate') in parentheses. * = no clear peak developed in these intervals.

No	Identification	Known age	Depth (cm)	Concentration	Bpeat age
0	Öræfajokull-1362?	588	8–12	ND	~779–574 (~680)
1	Hekla-1158?	792	14.5	3340	820–724 (766)
2	**Hekla-1**	846	16.5	1810	861–765 (804)
3	**Mixed, 'AD 860'?**	?	36–38	1590	1270–1133 (1194)
4	Hekla-3	*c.* 3000	120.5	8650	3150–3082 (3123)
5	Kebister?	*c.* 3750	176.5	310	3886–3750 (3821)
6	**Hekla-4?**	*c.* 4260	200.5	12720	4200–4009 (4120)
7			240–247	200–8000*	~4841–4432 (~4662)
8			368–372	ND	~5808–5631 (~5667)
9			384–387	860–7670*	~5931–5726 (~5771)
10	**Lairg-A**	*c.* 6950	436.5	1240	6803–6544 (6735)

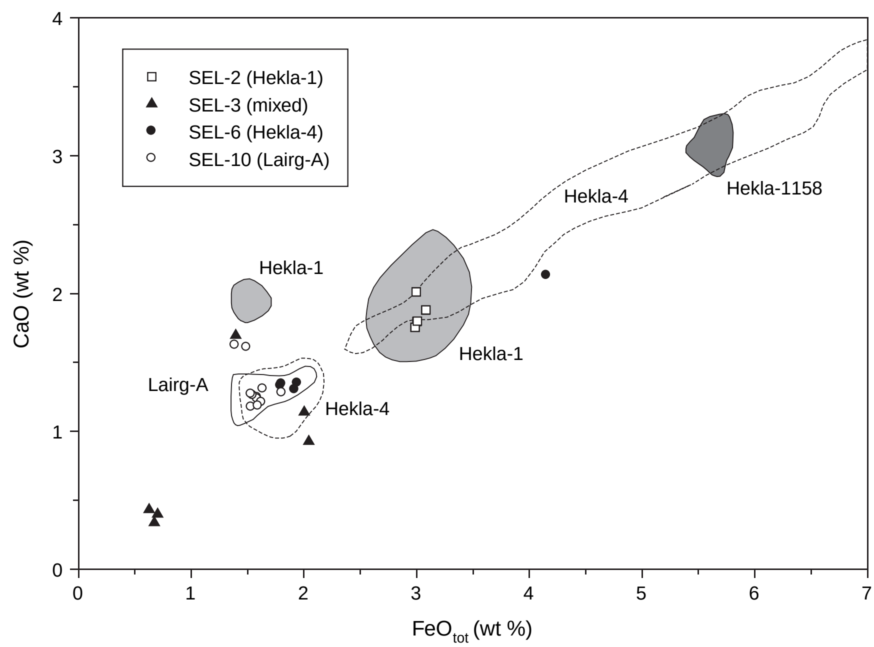

Fig. 6. CaO/FeO$_{tot}$ plot of four tephras in the Sellevollmyra sequence. The fields mark the known composition of the Hekla-1, Hekla-1158, Hekla-4 and Lairg-A tephras (data mainly from Tephrabase; www.tephrabase.org).

most of the mire herbs; PARZ M3, 322–206 cm, 5340–4220 cal. yr BP, with a medium high PAR ending with a rise in the Cyperaceae curve and PARZ M4, 206–0 cm, 4220–0 cal. yr BP. For the terrestrial, regional pollen taxa, PSIMPOLL distinguishes four PAR zones: differing temporally from the mire vegetation zones. PARZ T1, >440–434 cm, >6820–6650 cal. yr BP, which is characterized by a very high PAR of trees and grasses; PARZ T2, 434–426 cm, 6650–6410 cal. yr BP, which is characterized by a fall in most pollen taxa; PARZ T3, 426–183.5 cm, 6410–3910 cal. yr BP, with wiggling but a high PAR for most of the taxa; and PARZ T4, 183.5–0 cm, 3910–0 (?) cal. yr BP, where the accumulation rates for most taxa, even for supposedly long-distance transported pollen such as pine, decline to a low and persistent level. There is, however, a minor increase about the 110–100-cm level, where a hiatus is included. PAR are a function of the age scale. In particular there is one interval where the PAR might be influenced by dating irregularities: there is only one ^{14}C date between 434 and 385 cm (6650–5770 cal. yr BP), resulting in a suboptimal age model. However, even if

Table 5. Major oxide percentages in tephra from Sellevollmyra, determined by electron microprobe analyses. Analytical totals below 93% have been discarded. An empirical correction was applied to reduce to the P_2O_5 figure because of overlap with CaO counts (P. Hill, pers. comm. 2004).

Tephra layer, depth	SiO_2	TiO_2	Al_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Correlation
SEL-2, 16–17 cm	71.65	0.18	14.49	3.00	0.13	0.09	2.01	4.65	2.83	0.00	99.05	Hekla-1
	69.18	0.17	13.57	3.08	0.17	0.11	1.88	4.56	2.66	0.00	95.37	Hekla-1
	68.47	0.21	12.78	3.00	0.10	0.14	1.80	4.40	2.64	0.00	93.56	Hekla-1
	68.29	0.15	13.48	2.99	0.14	0.14	1.75	4.83	2.59	0.00	94.35	Hekla-1
Mean (n =4)	69.40	0.18	13.58	3.02	0.13	0.12	1.86	4.61	2.68	0.00	95.58	Hekla-1
1 σ	1.34	0.02	0.61	0.04	0.02	0.02	0.10	0.15	0.09	0.00		
SEL-3, 37–38 cm	75.65	0.12	13.04	0.67	0.01	0.03	0.34	3.48	4.65	0.08	98.06	Uncorr.
	75.53	0.27	12.55	2.04	0.00	0.18	0.93	3.98	3.67	0.09	99.24	AD 860 A?
	74.97	0.28	12.91	2.00	0.06	0.17	1.14	2.02	3.82	0.16	97.53	AD 860 A?
	73.43	0.17	14.77	1.40	0.02	0.40	1.70	4.39	3.05	0.06	99.38	AD 860 B?
	73.27	0.08	12.45	0.63	0.00	0.06	0.43	4.07	4.12	0.00	95.12	Uncorr.
	72.87	0.09	12.31	0.70	0.06	0.00	0.40	3.58	4.56	0.00	94.56	Uncorr.
SEL-6, 200–201 cm	75.59	0.09	13.15	1.80	0.11	0.02	1.34	2.79	2.78	0.00	97.66	Hekla-4
	75.13	0.07	12.99	1.94	0.14	0.03	1.35	4.10	2.93	0.00	98.67	Hekla-4
	72.54	0.12	11.66	4.15	0.03	0.42	2.13	3.40	3.93	0.00	98.38	Hekla-4
	72.30	0.07	12.94	1.79	0.09	0.02	1.33	4.33	2.93	0.01	95.80	Hekla-4
	71.62	0.08	12.63	1.92	0.05	0.03	1.30	3.85	2.56	0.01	94.04	Hekla-4
SEL-10, 436–437 cm	74.40	0.06	13.72	1.39	0.00	0.07	1.63	4.86	2.22	0.00	98.35	Lairg-A
	74.14	0.09	12.60	1.59	0.05	0.04	1.25	4.03	2.84	0.00	96.62	Lairg-A
	74.02	0.07	12.27	1.53	0.02	0.07	1.27	4.13	2.74	0.07	96.20	Lairg-A
	73.87	0.05	12.66	1.80	0.08	0.04	1.28	4.27	2.79	0.00	96.85	Lairg-A
	72.63	0.07	12.33	1.64	0.11	0.05	1.31	4.02	2.60	0.04	94.81	Lairg-A
	72.30	0.07	12.40	1.53	0.08	0.04	1.18	3.79	2.58	0.00	93.97	Lairg-A
	72.23	0.03	13.32	1.49	0.09	0.05	1.61	5.29	2.31	0.00	96.44	Lairg-A
	72.07	0.06	12.46	1.59	0.12	0.08	1.18	4.14	2.80	0.01	94.52	Lairg-A
	71.99	0.06	12.28	1.59	0.07	0.03	1.24	4.68	2.74	0.01	94.67	Lairg-A
	71.83	0.09	12.40	1.62	0.08	0.02	1.21	4.03	2.70	0.02	94.02	Lairg-A
	71.40	0.08	12.01	1.55	0.07	0.08	1.26	4.07	2.49	0.05	93.08	Lairg-A
Mean (n =11)	72.90	0.07	12.87	1.47	0.04	0.08	1.44	4.47	2.36	0.03	95.70	Lairg-A
1 σ	1.08	0.02	0.50	0.10	0.04	0.02	0.16	0.45	0.20	0.02		

Table 6. Calendar year estimates of the Hekla-4 and Lairg-A tephras obtained from the Sellevollmyra sequence compared with other studies from northwest Europe. Best age estimates in parentheses. * =midpoint ages.

Reference	Area	Type of date	Age range (cal. yr BP)
Hekla-4			
This study	N Norway	Bayesian	4200–4009 (4120)
Pilcher *et al.* (1995)	N Ireland	Combined ^{14}C dates of peat	4150–4360 (4260)
Zillén *et al.* (2002)	SW Sweden	Varved lake sediments	4500–4290 (4390*)
Dugmore *et al.* (1995)	Scotland	Combined ^{14}C dates of peat	4420–4080
Larsen & Thorarinsson (1977)	Iceland	?	4270–4150
Lairg-A			
This study	N Norway	Bayesian	6803–6544 (6735)
Bergman *et al.* (2004)	C Sweden	Combined ^{14}C dates of peat	7270–6650
Pilcher *et al.* (1996)	N Ireland	Combined ^{14}C dates of peat	6998–6808 (6903)*

using rough, interpolated age models, interpolating between the assumed Hekla-4 and Lairg-A dates similar PAR are achieved in this interval. The period before *c.* 5700 cal. yr BP (the Atlantic/Subboreal transition) is normally considered to belong to the Holocene optimum (Megathermal), even though Helama *et al.* (2004) have recorded two pine forest line regressions between 6800 and 6250 cal. yr BP and two very cold centuries between 6850 and 6150 cal. yr BP. The PAR minimum between 6140 and 5910 cal. yr BP (417–407 cm) could be related to a regional change in mires and a lake at northern Andøya, indicating a climatic deterioration (Vorren & Alm 1985). The rise of PAR after 5910 cal. yr BP may be the result of a climatic change characterized by warmer summers; in northern Finland the Holocene optimum of pine forests above the present forest limit occurred between 6000 and 4000 cal. yr BP (Seppä *et al.* 2002).

Table 7. Macrosubfossils in the peat interval 100–130 cm below surface (5-ml peat samples), each vertical centimetre: +, 1, 2, 3; abundance scale, subjectively assessed * = ^{14}C dated level.

Dated levels	Depth (cm)	*Vaccinium uliginosum* leaves	*Calluna vulgaris* shoots	*Andromeda polifolia* leaves	Ericales undiffer-entiated	*Eriophorum vaginatum* shoots, epidermis	Cyperaceae indet., roots, epidermis	Cyperaceae undiffer-entiated	*Rubus chamaemorus* seeds	*Sphagnum tenellum* leaves	*Sphagnum magellani-cum* leaves	Sphagna Acutifolia indet., leaves	*Sphagnum fuscum* leaves	*Sphagnum* undiffer-entiated	*Dicranum majus*	'Black spheroids'
*	100–101				3	2		2	1							+
	101–102				3	3		3								1
	102–103				1	3		3	1							1
*	103–104				2	3		3	1			1		1		1
	104–105				1	3		3				2		2		1
	105–106				1	3		3	1			1		1		1
	106–107				3	3		3	1			+		+		1
*	107–108	1			3	2		2	1							1+
	108–109	1+			3	3		3								1+
	109–110	1			2	3		3	1						1	1
	110–111	1			1	1	1	2		+	1	+	1	2		+
*	111–112						1	1					3	3		
	112–113						1	1					3	3		
*	113–114			1	1		1	1					3	3		
	114–115		+		+		1	1					3	3		
*	115–116		+		+		1	1					3	3		
	116–117		+		+		1	1					3	3		
*	117–118		+		+		1	1					3	3		
	118–119		1		1		1	1					3	3		
*	119–120		1		1		1+	1+					3	3		
*	120–121		1		1		1	1					3	3		
*	121–122		1		1		1	1					3	3		
*	122–123		1	1	3	2	+	2	1				1+	1+		+
*	123–124				3	2		2				+		+		+
	124–125				3	1		1	+			+		+		+
	125–126				3	1		1	+							1
	126–127				3	1		1	+							1
	127–128				3	2		2								1
	128–129				3	1		1	+			+		+		1
	129–130				3	2		2	+			+		+	+	1

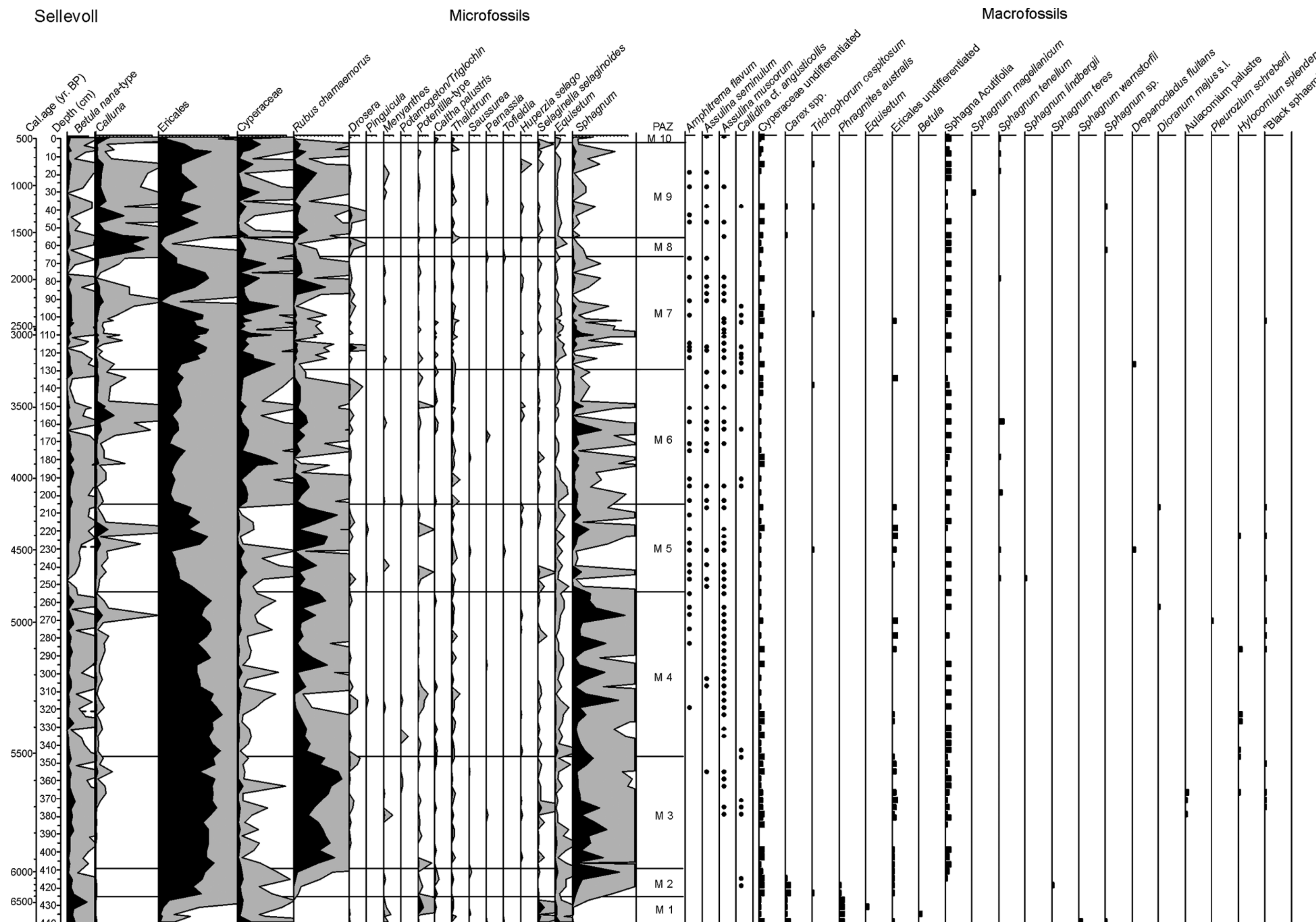

Fig. 7. Pollen and spore percentage diagram and macrofossil diagram of the mire vegetation. Solid horizontal lines are PSIMPOLL pollen assemblage zone limits.

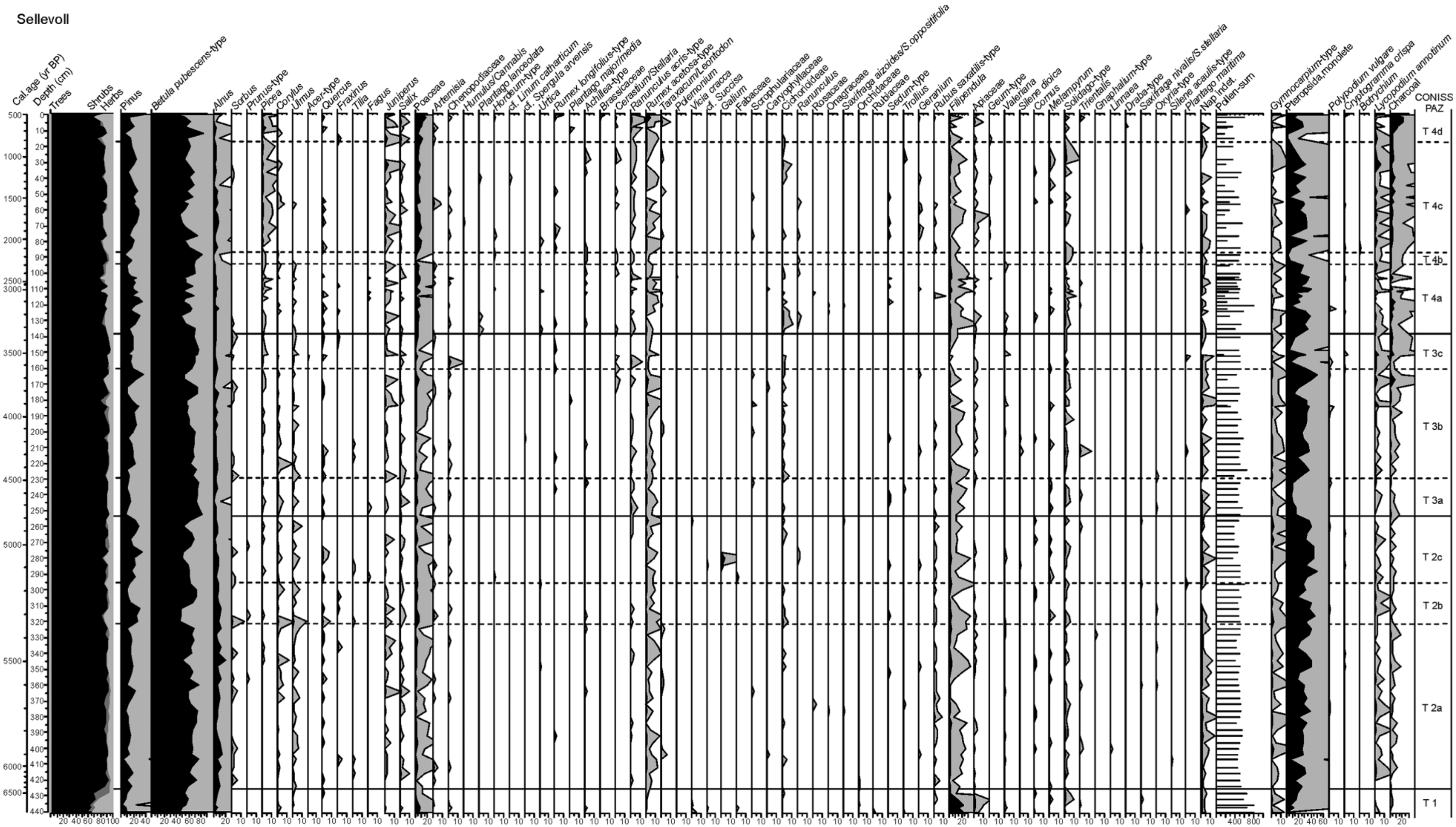

Fig. 8. Pollen and spore percentage diagram of the terrestrial vegetation. Solid horizontal lines are CONISS pollen assemblage zone limits.

The terrestrial PAR decline about 3910 cal. yr BP is probably realistic, seen with the background of tree-line data in the Finnish mountains east of Andøya (Helama *et al.* 2004; however, see also Helama *et al.* 2005) and the lower Nordic and Arctic sea temperatures, as a result of reduced inflow of Atlantic water to a level only slightly stronger than that of the Bølling–Allerød era (Ślubowska *et al.* 2006). The regional PAR decline about 3910 cal. yr BP should therefore be interpreted as an indication of regional forest-line lowering.

Total pollen concentration (grains/ml). – The total pollen accumulation curve (Fig. 4) and that of total PAR (Fig. 9) are very similar. The depression between *c.* 6230 and 5900 cal. yr BP (420–405 cm) is evident. The higher values around 5900–5640 (405–366 cm), 5550–5470 (353–342 cm), and 5390–5350 cal. yr BP (330–324 cm) may indicate periods of a comparatively warm climate. The two latter periods match fairly well with the humification peaks 5600–5480, respectively 5430 and 5330 cal. yr BP (Fig. 4, Table 3).

Discussion

Figure 10 displays the cal. yr BP ages of most local changes in the Sellevollmyra stratigraphy, many of them probably having been caused by climatic deteriorations during the late Holocene. In selecting time windows that are thought to be connected with climate deteriorations or climate changes, emphasis has been given to local mire development at the comparatively dry high plateau of Sellevollmyra, in particular low-humified peat intervals have been considered. In accordance with Barber (1981), we believe that even small changes in the peat decomposition and mire biota in ombrogenic mires are mainly the result of climatic impact, although there is a need for caution. For instance, humification is proven to be dependent on the species composition of the peat sample (Mauquoy *et al.* 2002a; Yeloff & Mauquoy 2006). One should also consider that formation of mire features such as string hummocks damming elongate pools and hollows will sustain moisture-demanding vegetation, which is intimately connected with soil frost conditions, which again depends on the balance between snow cover and winter temperatures; so there may be a complicated feedback system between the different climatic variables. The timing of changes in occurrence and abundance of the different Sellevollmyra climate proxies is generally not synchronous apart from a few time windows. Comparisons with some other investigations are summarized in Fig. 10. We must emphasize that many of these chronologies are only based on a few dates, the oldest ones on conventional dates only and very few with wiggle-matching. So the regional evidence for climate change has to be viewed with caution in the following context.

In Fig. 10, summer temperatures based on tree rings in northern Finland have been deduced from Helama *et al.* (2002). Pine tree-line depressions in northwestern Finland, probably mainly as a result of low summer temperatures and mild winters, have been dated by Helama *et al.* (2004). Winter temperatures combined with soil moisture based on solifluction dates from northern Finland have been provided by Matthews *et al.* (2005). Sea surface temperatures influencing the coastal climate were studied by Mikalsen *et al.* (2001), Husum & Hald (2004) and Ślubowska *et al.* (2006). Periods of high winter precipitation causing snow avalanches have been studied by Blikra & Selvik (1998). Winter storminess, deduced from studies of aeolian sand in peats by Björck & Clemmensen (2004), is a sign of climatic change. Summer humidity, as expressed through wet shifts and macrofossil changes in peat, have been studied by, for example, Nilssen & Vorren (1991), Vorren (2001), Borgmark (2005), Langdon & Barber (2005), Plunkett (2006) and de Jong *et al.* (2006). Emphasizing the lack of the regional 2850–2750 cal. yr BP event (Nilssen & Vorren 1991; Vorren 2001) because of a hiatus, it seems that the six most important climatic deteriorations/changes in the present material occur around 6410–6380, 6230–6050, 5340–5310, 4790–4710, 4220–4120 and 4000–3810 cal. yr BP. However, the periods around 5730–5640, 5470–5430, 4890–4820, 4380–4320, 3610–3580, 3140–3020, 2330–2220, 1950, 1530–1450, 1150, 730 and 600? cal. yr BP also play a part in the large-scale late Holocene climatic deterioration.

6410–6380 cal. yr BP (426–425 cm)

This level was not analysed for humification; however, local changes in the mire vegetation, confirming the change from mesotrophic to extremely oligotrophic mire vegetation (Ericales–Sphagna Acutifolia expansion), as well as changes in herb vegetation and pollen accumulation rates of regional trees and other terrestrial taxa, suggest a major climatic deterioration. This event might have induced the tree-line lowering in the Enontekiö region in northwestern Finland, some 200 km east of Andøya, between 6350 and 6250 cal. yr BP (Helama *et al.* 2004).

6230–6050 cal. yr BP (420–414 cm)

Locally there is a wet shift about 6200 cal. yr BP, with changes in the macrofossil and rhizopod/rotifer assemblages. There is a decrease of Cyperaceae and an increase of *Rubus chamaemorus*, confirming the oligotrophication process of the mire. Regional indications of a climatic change are the tree-ring results of Helama *et al.* (2002), suggesting a century with cold summers between 6250 and 6151 cal. yr BP. The

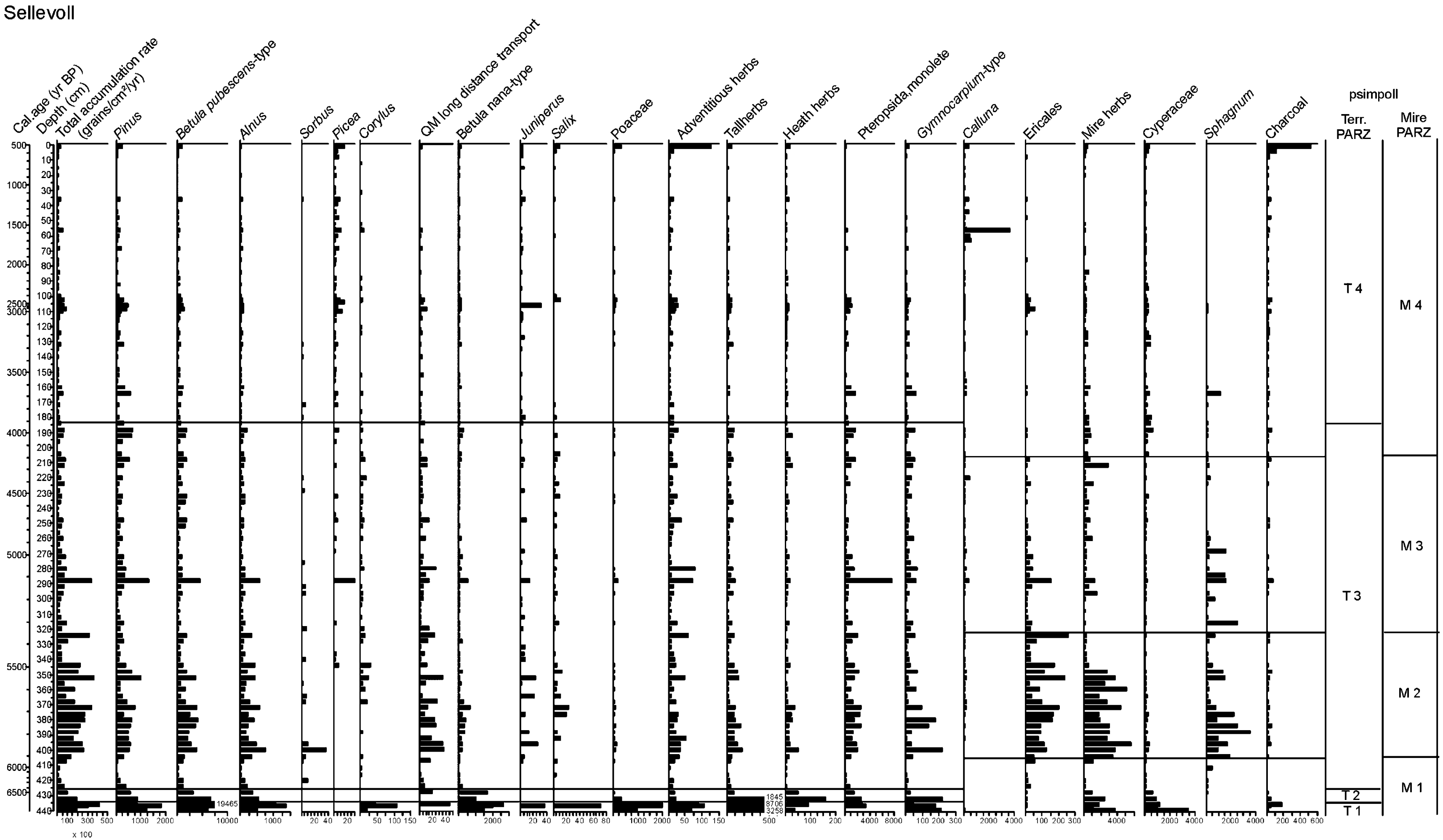

Fig. 9. Pollen and spore accumulation rate (influx) diagram with PSIMPOLL zonation for terrestrial and mire vegetation.

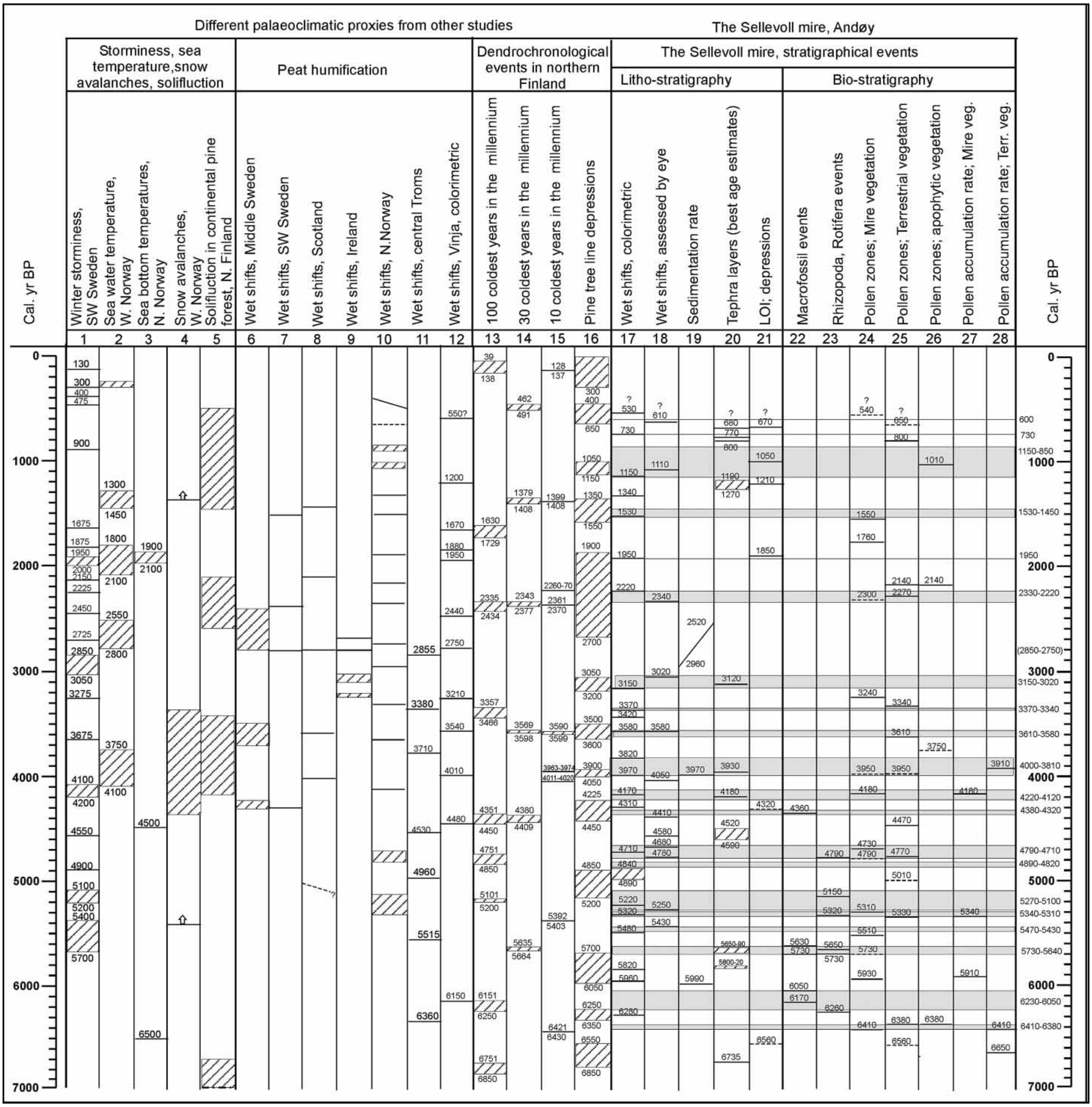

Fig. 10. Survey of the most important temporal changes in the different climate proxies of the Sellevollmyra peat sequence. Data on climatic events (mainly climatic deteriorations) recorded by different proxies from different sites in northern Europe are summarized in the columns to the left: 1 = Björck & Clemmensen (2004); 2 = Mikalsen *et al.* (2001); 3 = Husum & Hald (2004); 4 = Blikra & Selvik (1998); 5 = Matthews *et al.* (2005); 6 = Borgmark (2005); 7 = de Jong *et al.* (2006); 8 = Langdon & Barber (2005); 9 = Plunkett (2006); 10 = Nilssen & Vorren (1991); 11 = Vorren (2001); 12 = this paper; 13–15 = Helama *et al.* (2002); 16 = Helama *et al.* (2004); 17–28 = this paper.

low PAR and pollen concentration rates between *c.* 6140 and 5910 cal. yr BP may be the result of a regional climatic deterioration. Pollen diagrams from three islands east of Andøya and from the northern part of Andøya (Vorren & Alm 1985) show marked changes, such as oligotrophication in the mires [start or clear increase of Ericales (coll.), *Rubus chamaemorus*, *Calluna* and *Sphagnum*], and, at northern Andøya (Endletvann), in lacustrine sediments there is a local increase of *Myriophyllum alterniflorum* accompanied by a decrease in ferns and regional tree birch pollen. The Vinja peat sequence shows a marked wet shift between 6110 and 6040 cal. yr BP (Fig. 5).

5730–5640 cal. yr BP (380–367 cm)

A wet shift occurs around 5700 cal. yr BP (376 cm). A layer of the slightly mineral soil water-demanding moss *Aulacomnium palustre* occurs at *c.* 5730–5640 cal. yr BP, approximately contemporaneous with two tephra layers. There is also a fall in the pollen concentration and accumulation rates about 5730 cal. yr BP (380 cm), together with changes in the testate amoeba fauna and the local mire vegetation. The event is metachronous to a fall in the pine tree line in northern Finland between 5950 and 5700 cal. yr BP (Helama *et al.* 2004). Between 5700 and 5400 cal. yr BP there was increased winter storminess in southwest Sweden, probably as a result of an expansion of the polar vortex (Björck & Clemmensen 2004). The local changes in the Sellevoll mire might be the result of an erection of a strictly local draining soak. The PAR together with the local changes indicate a climatic forcing of the changes, maybe an increase in precipitation, and not a temperature decline.

5470–5430 cal. yr BP (342–343 cm)

Locally there is a wet shift about 5480 cal. yr BP and a decline of *Rubus chamaemorus* responding to a change in the environment. There is also a fall in the total pollen concentration. This event parallels the middle one of three water level rises in Lake Constance at the border of Switzerland, Austria and Germany (Magny *et al.* 2006), corresponding to a tri-partite solar-forced cooling of the climate indicated by increases in atmospheric ^{14}C concentration (Blaauw *et al.* 2004). The start of the mid-Holocene snow avalanches in western Norway (Blikra & Selvik 1998) suggests a clear deterioration of the winter climate from 5400 cal. yr BP. One of the coldest decades during the last 7500 years was recorded by dendrochronology between 5403 and 5392 cal. yr BP (Helama *et al.* 2002).

5340–5310 cal. yr BP (322–317 cm)

Simultaneous changes at Sellevollmyra occur within humification, Rhizopoda (first *Amphitrema flavum* record), regional (terrestrial) pollen percentages (low A.P., high pine and low tree birch) and mire pollen influx (Ericales decrease) data. There is also a fall in the total pollen concentration. A marked fall in the (grey) alder curve at the neighbouring island to the east, Senja (Bakkemyra), happened about 5300–5250 cal. yr BP (Vorren & Alm 1985). This event appears to be contemporaneous with the third possibly solar-forced water level rise in Lake Constance reported by Magny *et al.* (2006).

5270–5100 cal. yr BP (311–297 cm)

Two marked wet shifts occur in this period. The Ericales curve declines from its all-time high and the *Rubus chamaemorus* rise and *Assulina seminulum* occurrences indicate increased moisture in the mire. The start of a continuous *Amphitrema flavum* curve in the Sellevollmyra sequence occurs *c.* 5100 cal. yr BP. *Amphitrema flavum* is one of the most moisture-demanding Rhizopoda (in peat with more than 95% water content; Tolonen *et al.* 1992). Regionally, there is a pine tree-line lowering in northwestern Finland between *c.* 5200 and 4850 cal. yr BP (Helama *et al.* 2004) and a summer-cold century between 5200 and 5101 cal. yr BP (Helama *et al.* 2002).

4890–4870 and 4840–4820 cal. yr BP (263–261 and 259–257 cm)

A marked wet shift occurs within each of these two periods, which are divided by a 30-year long warmer event according to the humification data. According to Helama *et al.* (2002), there was a summer-cold century between 4850 and 4751 cal. yr BP. A regional wet shift for the district northeast of Andøya has been dated prior to this level (Vorren 2001; 4950 cal. yr BP). During this period, our depth–age model also suggests a notable decline in accumulation rate (corroborating the inferred wetter conditions). This period may have been the trigger of the larger changes that occur in the next time slice.

4790–4710 cal. yr BP (255–247 cm)

There is a moderate wet shift about 4710 cal. yr BP in the Sellevollmyra sequence. However, large changes in the mire flora occur prior to that; Ericales and *Sphagnum* microfossils decline radically from the 255-cm level. *Assulina seminulum* occurs frequently from this level on, and there is a temporary rise in the Cyperaceae curve, all pointing towards increased local moisture at the top plateaux of the raised bog. The *Betula* curve rises towards an absolute late Holocene maximum and ferns experience a sudden and long-lasting depression. These events, most probably climatically induced, do not seem to have any counterparts in the region nor in a wider geographical context. An interpretation of the data would be that they point towards the onset of a period of continentalization of the climate: warm summers and cold winters, with accelerated formation of hollows, pools and elongate narrow hummocks surrounding the wet features.

4380–4320 cal. yr BP (222–217 cm)

About 4380 cal. yr BP the macrofossil *Hylocomium splendens* terminates, and about 4330 cal. yr BP (218 cm) there is a marked wet shift. However, these indications of a still more humid climate are not supported by the *Calluna* and Ericales pollen curves, which indicate a locally drier phase. There is a slightly increased mineral content in the peat after 4320 cal. yr BP (Fig. 4; 217 cm), which may indicate deposition of aeolian sand particles, although they have not been microscopically determined as such. Large sand dunes exist on the island, the closest ones at Ramså *c.* 5 km north-northeast of Sellevollmyra. Björck & Clemmensen (2004) and de Jong *et al.* (2006) consider aeolian sand influx as a proxy for winter storminess (niveo-aeolian transport) and increased cyclonic activity. In southwest Sweden, these authors have not recorded increased aeolian sand influx around 4360–4320 cal. yr BP. However, a wet shift is recorded there (de Jong *et al.* 2006) and in middle Sweden (Borgmark 2005; Jessen 2006). The period 4350–3350 cal. yr BP is the main period of snow avalanches in western Norway (Blikra & Selvik 1998).

4220–4120 cal. yr BP (209–201 cm)

This time window includes a wet shift at 205 cm and a substantial change in the mire flora towards moister conditions (Cyperaceae increases and the Ericales PAR decreases, probably connected with a further expansion of the hollow area at the bog). During the period 4250–4050 cal. yr BP, the pine tree limit in northern Finland receded (Helama *et al.* 2004). Increased storminess in the winters occurred between 4200 and 4100 cal. yr BP in southwest Sweden (Björck & Clemmensen 2004). Solifluction data from northern Finland (Matthews *et al.* 2005) also support the impression of a supra-regional climatic event with severe winters. Around this period a major climate change occurred in tropical regions (e.g. Drysdale *et al.* 2006).

4000–3810 cal. yr BP (191–176 cm)

The start of a wet shift is dated at *c.* 3970 cal. yr BP. The most striking changes occur about 3900 cal. yr BP (183 cm), with a strong and lasting depression of the PAR, particularly of trees (Fig. 9), which we interpret as a general reduction of the forested area (tree-line lowering) caused by climatic deterioration. The only possible indication of a climatic deterioration in the bog vegetation is a Cyperaceae peak *c.* 3910 cal. yr BP combined with a *Rubus chamaemorus* minimum, indicating extended hollow formation. Particularly low summer temperatures occurred between 4020 and 4011 and between 3974 and 3963 cal. yr BP (Helama *et al.* 2002). The pine tree line in northern Finland retreated radically from its early Holocene highest position in response to cooler and moister conditions after 4000 cal. yr BP (Seppä *et al.* 2002) or slightly before 4000 cal. yr BP (Helama *et al.* 2004). Temperatures in the Nordic and Barents seas declined around 4000 cal. yr BP, and the period 4000–2000 cal. yr BP is called the 'neoglacial cooling' by Ślubowska *et al.* (2006).

3610–3580 (−3450) cal. yr BP [160–159 (−147) cm]

A marked wet shift is recorded at *c.* 3580 cal. yr BP and the low-humified interval persists until 3450 cal. yr BP, contemporaneous with a *Betula pubescens* and A.P. peak, at the expense of herbs, including ferns. *Sphagnum* spores decline towards a second minimum since the initiation of the bog peat. Helama *et al.* (2004) record a tree-line depression between 3600 and 3500 cal. yr BP in northern Finland. Björck & Clemmensen (2004) record an increase in winter storms at 3675 cal. yr BP. A distinct change to wetter conditions is also seen in many European bogs at around 3700–3500 cal. yr BP (e.g. Anderson 1998; Borgmark & Wastegård in prep.).

3370–3350 cal. yr BP (141–139 cm)

A wet shift here corresponds with regional wet shifts about 3380–3350 cal. yr BP (Nilssen & Vorren 1991; Vorren 2001). The most active period of snow avalanches in western Norway (Blikra & Selvik 1998) and solifluction in northern Finland (Matthews *et al.* 2005) terminates *c.* 3400–3300 cal. yr BP, indicating a cool and particularly moist and snow-rich climatic regime 4300–3300 cal. yr BP.

3150–3020 cal. yr BP (123–113 cm)

A marked wet shift occurs about 3150 cal. yr BP and low-humified peat persists until 3020 cal. yr BP. In northwestern Finland there was a pine tree-line depression about 3200–3000 cal. yr BP (Helama *et al.* 2004).

2850–2750 cal. yr BP (hiatus, probably at 110 cm)

This period is absent from Sellevollmyra because of a hiatus but is recorded as a wet shift regionally (Nilssen & Vorren 1991; Vorren 2001), Vinja (Fig. 5) and world-wide (van Geel *et al.* 1996, 1999).

2330–2220 cal. yr BP (96–91 cm)

A marked wet shift occurs at the upper end of this time window, about 2220 cal. yr BP. Mire vegetation (CONISS) indicates a zone limit in the mire pollen sequence about 2330 cal. yr BP (97 cm), where *Calluna* and Cyperaceae increase and Ericales (mainly *Empetrum*) declines towards zero. The regional vegetation about 2250 cal. yr BP is characterized by an increase in *Betula pubescens* and a corresponding fall in herbs, including ferns. Helama *et al.* (2002) record a cool period around 2265 cal. yr BP in northern Finland. The tree line in northwestern Finland was low during the entire period 2700–2050 cal. yr BP (Helama *et al.* 2004). The period 2650–2100 cal. yr BP is one of the most active solifluction periods in northern Finland (Matthews *et al.* 2005). Björck & Clemmensen (2004) recorded increased winter storminess about 2225 cal. yr BP.

1950 cal. yr BP (78 cm)

A wet shift is recorded in the Sellevollmyra sequence. This event is probably parallel with a regional wet shift dated at 1900 cal. yr BP (Nilssen & Vorren 1991) and 1940–1880 cal. yr BP at Vinja (Fig. 5). Björck & Clemmensen (2004) recorded increased winter storminess in southwest Sweden about 2000–1950 and 1875 cal. yr BP. Sea bottom temperatures in the Malangen fjord northeast of Andøya were 1–2°C colder than at present during the period 2100–1900 cal. yr BP, with the coldest phase just before 1900 cal. yr BP (Husum & Hald 2004; K. Husum, pers. comm. 2005). In western Norway a period of cooling of the seawater is dated at 2100–1800 cal. yr BP (Mikalsen *et al.* 2001).

1530–1450 cal. yr BP (55–51 cm)

A marked wet shift occurs at Sellevollmyra about 1530 cal. yr BP. A marked decline of *Calluna* after its absolute maximum in the whole sequence, occurring together with an increase of Ericales (mainly *Empetrum*) about 1490 cal. yr BP (53 cm), may have been climatically induced. A regional wet shift in northern Norway is dated at 1560 cal. yr BP (Nilssen & Vorren 1991), while in southwest Sweden (de Jong *et al.* 2006) and Scotland (inferred from Langdon & Barber 2005) there are also wet shifts and/or changes in the macrofossil composition about 1550–1450 cal. yr BP. Cold sea temperatures in western Norway occurred later: 1450–1300 cal. yr BP (Mikalsen *et al.* 2001), synchronously with a pine forest retreat 1450–1350 cal. yr BP (Helama *et al.* 2004). Summer-cold 30- and 10-year periods occurred about 1400 cal. yr BP (Helama *et al.* 2002). The world-wide cold period AD 541–550 (1409–1400 cal. yr BP), which is also recorded dendrochronologically in northern Norway (Kirchhefer 2005), is not recorded by any mire proxies in the Sellevollmyra peat based on our age model. There may be a wet shift in German and Danish bogs at this time (Barber *et al.* 2004).

1150–840 cal. yr BP (35–19 cm)

Except for a marked wet shift dated at 1150 cal. yr BP, or a little later according to ocular judgement, there are no other proxies in the Sellevollmyra sequence to confirm this assumed cool period. At Vinja, there is a wet shift dated at about 1200–1150 cal. yr BP, and regionally a wet shift about 1000 cal. yr BP has been suggested (Nilssen & Vorren 1991). Helama *et al.* (2004) record a pine forest retreat between 1150 and 1050 cal. yr BP. In bogs in south-central Sweden, the most pronounced wet phase during the last millennia is recorded between *c.* 1200 and 1050 cal. yr BP (Borgmark & Wastegård in prep.).

730–? cal. yr BP (13–9 cm) and 600?–? cal. yr BP (5–0 cm)

These intervals are characterized by low humified peat in Sellevollmyra. For further discussion it must be emphasized that dates younger than *c.* 840 cal. yr BP are unreliable in our age model. It is not possible to connect the earliest wet shift with any dendrochronologically known climatic deterioration. However, there is a period between AD 1000 and 1450 with a lack of pine stems in the region east of Andøya. The reason for this may be a climatic depression in the 12th century (Kirchhefer 2005). Based on pine dendrochronology from Torneträsk, northern Sweden, Grudd (2006) found that a notably summer-cold period occurred around AD 1150 (his graphs show minimum ring-widths/inferred low summer temperatures in the first part of the 12th century). A regional wet shift occurred about 600 cal. yr BP (Nilssen & Vorren 1991) and at Vinja about 550 cal. yr BP (Fig. 5). The period 650–600 cal. yr BP is one with a pine forest retreat (Helama *et al.* 2004). According to dendrochronology, this period is not characterized by low temperatures, neither in the Andøy municipality (Kirchhefer 2001; A. J. Kirchhefer, pers. comm. 2006) nor in northern Finland (Helama *et al.* 2002). However, in the interior of northern Norway east of Andøya, Kirchhefer (2005) has recorded a climatic depression centred about AD 1460 (*c.* 500 cal. yr BP), which is also recorded elsewhere by dendrochronologists (A. J. Kirchhefer, pers. comm. 2006). In eastern Greenland there was a glacier advance somewhat earlier, between 650 and 550 cal. yr BP (Geirsdóttir *et al.* 2000), which was connected with a fall in sea temperatures. The GRIP core also shows a cold spell between AD 1300 and 1400, and a transition to wetter conditions is recorded in bogs in northern Germany and Denmark at this time (Barber *et al.* 2004).

Tephra and environmental changes

It is a well-known fact that large volcanic eruptions may generate significant global cooling during the years following the eruption. One example is the Laki eruption in Iceland 1783–1784, when sulphuric acid aerosol-forced cooling in Europe and other regions caused crop failure and mortality crises (e.g. Stothers 1996; Witham & Oppenheimer 2004). Volcanic impacts have also been reported in distal areas in connection with prehistoric eruptions, most notably the Hekla-4 event (*c.* 4260 cal. yr BP; Pilcher *et al.* 1995) on the British Isles (Blackford *et al.* 1992; Wells *et al.* 1997), while other studies have failed to record significant changes or are less conclusive (e.g. Hall *et al.* 1994; Caseldine *et al.* 1998). A possible link between tephra fall-out and increasing bog wetness can be seen at 384–387 cm in the Sellevollmyra sequence, dated at 5765–5785 cal. yr BP. An undetermined tephra (SEL-9) occurs contemporaneously with the start of a peat layer characterized by *Aulacomnium palustre*, indicating a rise of the groundwater table or formation of a local soak. This moss layer terminates contemporaneously with another undetermined tephra layer (SEL-8, 372–368 cm, about 5650 cal. yr BP), although this layer does not have a high concentration of ash particles. The causes of the groundwater rise/formation of a local soak may have been a climatic deterioration. However, other data indicate a warm period. In the Sellevollmyra sequence, the peak concentration of the Hekla-4 tephra is found at 200–201 cm and is dated to *c*. 4120 cal. yr BP. This is slightly younger but still within confidence margins of earlier dates of this tephra (Table 6). However, one of the most important changes in the bog development, such as the rise of the Cyperaceae curve and the corresponding decline of Ericales and *Rubus chamaemorus*, occurs at the 206-cm level, about 40 years prior to the Hekla-4 event and clearly below the first occurrence of the tephra. Admittedly, the macrofossil and Rhizopoda–Rotifera (*Callidina* reoccurrence) assemblages indicate changes in a period centred about 4100 cal. yr BP (198 cm), but these curves have a low temporal resolution and, according to van Geel (1978), *Callidina* has no special indicator value. A direct link between the Hekla-4 event and increasing bog wetness is thus difficult to infer.

Conclusions

The Bayesian wiggle-match of 35 ^{14}C dates and two historically dated tephra layers permits a high degree of temporal resolution of the Sellevollmyra peat sequence, covering almost 7000 years of the mid to late Holocene.

There seems to be a general cooling trend throughout the entire sequence, where cooler spells interchange with warmer periods. The proxy diagrams (Figs 7, 8, 9) indicate that the main cooling of the climate happened stepwise but with special strength in the periods around 6400, 6200, 5340, 4790 (although this event may have had a different climatic character) and 4220–3810 cal. yr BP, if not considering the Subboreal/Subatlantic transition. However, the peat accumulation rate (Fig. 4) is slower after the hiatus between 2960 and 2520 cal. yr BP, possibly indicating a less favourable climate after 2520 cal. yr BP.

The changes between *c.* 4200 and 3800 cal. yr BP most probably induced the hummock–hollow–pool pattern that characterizes Sellevollmyra today. This indicates that soil frost activity increased (colder winters), contributing to the formation of such mire features. A similar event, although temporary, occurred between 4790 and 4640 cal. yr BP.

The PAR decline in regional forest vegetation about 3900 cal. yr BP caused an enduring change of the regional vegetation. This decline is probably connected with a lowering of the forest limits and a decrease of the total forested area in the region.

Some of the tephra layers are seemingly connected with changes in the vegetation indicating climatic deteriorations, such as the Hekla-4 event. However, the temporal scale established here indicates that the climatic changes took place some decades before the Hekla-4 eruption.

Acknowledgements. – We want to extend our thanks to the University of Amsterdam, the ^{14}C labs of Groningen, Trondheim and Uppsala for the dates; Dr. Andreas Kirchhefer, Univ. of Tromsø for comments on dendrochronology; Dr. Kathrine Husum, Univ. of Tromsø for comments on sea temperatures; M.Sc. Beret M. Vorren, Oslo, for humification analyses of the Vinja core; Mr. Roger Malm, Sweden for field assistance; M.Sc. Ellen Elverland, M.Sc. Virginie Ramasco, Univ. of Tromsø for preparation work; Ms Tove Midtun, University of Tromsø for drawing assistance; and to the referees Dr. Dmitri Mauquoy and Dr. Jon R. Pilcher for constructive criticism.

References

Aaby, B. 1986: Palaeoecological studies in mires. *In* Berglund, B. (ed.): *Handbook of Palaeoecology and Palaeohydrology*, 145–164. Wiley & Sons, Chichester.

Aartolahti, T. 1965: Oberflächenformen von Hochmooren, und ihre Entwicklung in Südwest-Häme und Nord-Satakunta. *Fennia 93*, 1–268.

Anderson, D. E., Binney, H. A. & Smith, M. 1998: Evidence for abrupt climatic change in northern Scotland between 3900 and 3500 calendar years BP. *The Holocene 8*, 97–103.

Aune, B. 1993: Temperaturnormaler, normalperiode 1961–90. *DNMI-Klima Report 02/93*, 1–63.

Barber, K. E. 1981: *Peat Stratigraphy and Climate Change: A Palaeoecological Test of the Theory of Cyclic Peat Bog Regeneration*. 219 pp. Balkema, Rotterdam.

Barber, K. E., Chambers, F. M. & Maddy, D. 2004: Late Holocene climatic history of northern Germany and Denmark: peat macrofossil investigations at Dosenmoor, Schleswig-Holstein, and Svanemose, Jutland. *Boreas 33*, 132–144.

Beijerinck, W. 1947: Zadenatlas der nederlandsche flora. *Mededeeling van het Biologisch Station te Wijster 30*, 1–308.

Bennett, K. D. 1994: Recent plant nomenclatural changes and pollen morphology in the British Isles. *Quaternary Newsletter, Quaternary Research Association, London, 73*, 1–6.

Bennett, K. D. 1996: Determination of the number of zones in a biostratigraphical sequence. *New Phytologist 132*, 155–170.

Bennett, K. D. 2005: *Documentation for Psimpoll 4.25 and Pscomb 1.0.3.C Programs for Plotting Pollen Diagrams and Analysing Pollen Data. Software Manual*. http://www.kv.geo.uu.se. Accessed Dec. 7, 2006.

Bergman, J., Wastegård, J., Hammarlund, D., Wohlfarth, B. & Roberts, S. J. 2004: Holocene tephra horizons at Klocka Bog, west-central Sweden: aspects of reproducibility in subarctic peat deposits. *Journal of Quaternary Science 19*, 241–249.

Björck, S. & Clemmensen, L. 2004: Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? *The Holocene 14*, 677–688.

Blaauw, M., Bakker, R., Christen, J. A., Hall, V. A. & van der Plicht, J. in press: A Bayesian framework for age-modelling of radiocarbon-dated peat deposits. Case studies from the Netherlands. Radiocarbon.

Blaauw, M. & Christen, J. A. 2005: Radiocarbon peat chronologies and environmental change. *Applied Statistics 54*, 805–816.

Blaauw, M., van Geel, B. & van der Plicht, J. 2004: Solar forcing of climate change during the mid-Holocene: indications from raised bogs in the Netherlands. *The Holocene 14*, 35–44.

Blackford, J., Edwards, K., Dugmore, A., Cook, G. & Buckland, P. 1992: Icelandic volcanic ash and mid-Holocene Scots pine (*Pinus sylvestris*) pollen decline in northern Scotland. *The Holocene 2*, 260–265.

Blikra, L. H. & Selvik, S. F. 1998: Climatic signals recorded in snow avalanche-dominated colluvium in western Norway: depositional facies successions and pollen records. *The Holocene 8*, 631–658.

van den Bogaard, C., Dörfler, W., Glos, R., Nadeau, M.-J., Grootes, P. M. & Erlenkeuser H. 2002: Two tephra layers bracketing late Holocene paleoecological changes in northern Germany. *Quaternary Research 57*, 314–324.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. & Bonani, G. 2001: Persistent solar influence on North Atlantic climate during the Holocene. *Science 294*, 2130–2136.

Borgmark, A. 2005: Holocene climatic variability and periodicities in south-central Sweden, as interpreted from peat humification analysis. *The Holocene 15*, 387–395.

Caseldine, C., Hatton, J., Huber, U., Chiverrell, R. & Woolley, N. 1998: Assessing the impact of volcanic activity on mid-Holocene climate in Ireland; the need for replicate data. *The Holocene 8*, 105–111.

Chambers, F. M., Daniell, J. R. G., Hunt, J. B., Molloy, K. & O'Connell, M. 2004: Tephrostratigraphy of An Loch Mór, Inis Oírr, western Ireland: implications for Holocene tephrochronology in the northeastern Atlantic region. *The Holocene 14*, 703–720.

Charman, D. J., Brown, A. D., Hendon, D. & Karofeld, E. 2004: Testing the relationship between Holocene peatland palaeoclimate reconstructions and instrumental data at two European sites. *Quaternary Science Reviews 23*, 137–143.

Davies, S. M., Branch, N. P., Lowe, J. J. & Turney, C. S. M. 2002: Towards a European tephrochronological framework for Termination 1 and the Early Holocene. *Philosophical Transactions of the Royal Society of London Series A, Mathematical, Physical and Engineering Sciences 360*, 767–802.

Drysdale, R., Zanchetta, G., Hellstrom, J., Maas, R., Fallick, A., Pickett, M., Cartwright, I. & Piccini, L. 2006: Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. *Geology 34*, 101–104.

Dugmore, A. J. 1989: Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine 105*, 168–172.

Dugmore, A. J., Cook, G. T., Shore, J. S., Newton, A. J., Edwards, K. J. & Larsen, G. 1995: Radiocarbon dating tephra layers in Britain and Iceland. *Radiocarbon 37*, 379–388.

Eneroth, O. 1951: Undersökning rörande möjligheterna att i fossilt materiale urskilja de olika *Betula-arternas* pollen. *Geologiska Föreningen i Stockholm Förhandlingar 73*, 343–390.

Fægri, K. & Iversen, J. 1989: *Textbook of Pollen Analysis.* 328 pp. Munksgaard, Copenhagen.

Førland, E. J. 1993: Nedbørnormaler, normalperioden 1961–90. *DNMI-Klima Report 39/93*, 1–63.

van Geel, B. 1978: A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands. *Review of Palaeobotany and Palaeoecology 25*, 1–120.

van Geel, B., Buurman, J. & Waterbolk, H. T. 1996: Archaeological and palaeological indications of an abrupt climate change in the Netherlands, and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science 11*, 451–460.

van Geel, B., Raspopov, O. M., Renssen, H., van der Plicht, J., Dergachev, V. A. & Meijer, H. A. J. 1999: The role of solar forcing upon climate change. *Quaternary Science Reviews 18*, 331–338.

Geirsdóttir, Á., Hardardóttir, J. & Andrews, J. T. 2000: Late-Holocene terrestrial glacial history of Miki and I. C. Jacobsen Fjords, East Greenland. *The Holocene 10*, 123–134.

Granlund, E. 1932: De svenska høgmossarnas geologi, deras bildningsbetingelser, utvecklingshistoria och utbredning jämte sambandet mellan högmossbildning och försumpning. *Sveriges Geologiska Undersökninger C 373*, 1–193.

Grimm, E. C. 1987: CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences 13*, 13–35.

Grimm, E. C. 1993: *TILIA 2.0 version b.4 (computer software)*. Illinois State Museum, Research and Collections Center, Springfield, IL.

Grimm, E. C. 2004: *TGView version 2.0.2 (computer software)*. Illinois State Museum, Research and Collections Center, Springfield, IL.

Grudd, H. 2006: Torneträsk tree-ring width and density AD 500–2004. A test of climatic sensitivity and a new 1500-year reconstruction of North Fennoscandian summers. *Dissertations from the Department of Physical Geography and Quaternary Geology 1, Stockholm University*, 1–17.

Gunnarson, B., Borgmark, A. & Wastegård, S. 2003: Holocene humidity fluctuations in Sweden inferred from dendrochronology and peat stratigraphy. *Boreas 32*, 347–360.

Hall, V. A., Pilcher, J. & McCormack, F. 1994: Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) decline in the north of Ireland: no correlation. *The Holocene 4*, 79–83.

Helama, S., Lindholm, M., Timonen, M. & Eronen, M. 2005: Mid- and late Holocene tree population density changes in northern Fennoscandia derived by a new method using megafossil pines and their tree-ring series. *Journal of Quaternary Science 20*, 567–575.

Helama, S., Lindholm, M., Timonen, M., Meriläinen, J. & Eronen, M. 2002: The supra-long Scots pine tree-ring record for Finnish Lapland. Part 2. Interannual to centennial variability in summer temperatures for 7500 years. *The Holocene 12*, 681–687.

Helama, S., Lindholm, M., Timonen, M., Meriläinen, J. & Eronen, M. 2004: Dendrochronologically dated changes in the limit of pine in northernmost Finland during the past 7.5 millennia. *Boreas 33*, 250–259.

Hendon, D. & Charman, D. J. 1997: The preparation of testate amoebae (Protozoa: Rhizopoda) samples from peat. *The Holocene 7*, 199–205.

Hunt, J. B. & Hill, P. G. 1993: Tephra geochemistry: a discussion of some persistent analytical problems. *The Holocene 3*, 271–278.

Husum, K. & Hald, M. 2004: A continuous marine record 8000–1600 cal. yr BP from the Malangenfjord, north Norway: foraminiferal and isotopic evidence. *The Holocene 14*, 877–887.

Jessen, C. A. 2006: The ups and downs of the Holocene: exploring relationships between global CO_2 and climate variability in the North Atlantic region. *Lundqua Thesis 55, 1–34.*

de Jong, R., Björck, S., Björkman, L. & Clemmensen, L. 2006: Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, SW Sweden. *Journal of Quaternary Science 21*, 905–919.

Kirchhefer, A. J. 2001: Reconstructions of summer temperatures from tree-rings of Scots pine (*Pinus sylvestris* L.) in coastal northern Norway. *The Holocene 11*, 41–52.

Kirchhefer, A. J. 2005: A discontinuous tree-ring record AD 320–1994 from Dividalen, Norway: inferences on climate and tree-line history. *In* G. Broll & B. Keplin (eds.): *Mountain Ecosystems. Studies in Treeline Ecology*, 219–235. Springer, Berlin.

Langdon, P. G. & Barber, K. E. 2005: The climate of Scotland over the last 5000 years inferred from multiproxy peatland records: inter-site correlations and regional variability. *Journal of Quaternary Science 20*, 549–566.

Larsen, G. 1981: Tephrochronology by microprobe glass analysis. *In* Self, S. & Sparks, R. S. J. (eds.): *Tephra Studies, Proceedings of the NATO Advanced Study Institute, Tephra Studies as a Tool in Quaternary Research*, 95–102. D. Reidel Publ. Co., Dordrecht.

Larsen, G. & Thorarinsson, S. 1977: H4 and other acid Hekla tephra layers. *Jökull 27*, 28–46.

Lid, J. & Lid, D. 1994: *Norsk Flora*. 1014 pp. Det norske Samlaget, Oslo.

Magny, M., Leuzinger, U., Bortenschlager, S. & Haas, J. N. 2006: Tripartite climate reversal in central Europe 5600–5300 years ago. *Quaternary Research 65*, 3–19.

Marshall, J., Kushnir, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J., McCartney, M., Saravanan, R. & Visbeck, M. 2001: North Atlantic climate variability: phenomena, impacts and mechanisms. *International Journal of Climatology 21*, 1863–1898.

Matthews, J. A., Seppälä, M. & Dresser, P. Q. 2005: Holocene solifluction, climate variation and fire in a subarctic landscape at Pippokangas, Finnish Lapland, based on radiocarbon-dated buried charcoal. *Journal of Quaternary Science 20*, 533–548.

Mauquoy, D., Engelkes, T., Groot, M. H. M., Markesteijn, F., Oudejans, M. G., van der Plicht, J. & van Geel, B. 2002a: High-resolution records of late Holocene climate change and carbon accumulation in two north-west European ombrotrophic peat bogs. *Palaeogeography, Palaeoclimatology, Palaeoecology 186*, 275–310.

Mauquoy, D., van Geel, B., Blaauw, M. & van der Plicht, J. 2002b: Evidence from northwest European bogs show 'Little Ice Age' climatic changes driven by variations in solar activity. *The Holocene 12*, 1–6.

Mauquoy, D., van Geel, B., Blaauw, M., Speranza, A. O. M. & van der Plicht, J. 2004: Changes in solar activity and Holocene climate shifts derived from ^{14}C wiggle-match dated peat deposits. *The Holocene 14*, 45–52.

Mikalsen, G., Sejrup, H. P. & Aarseth, I. 2001: Late-Holocene changes in ocean circulation and climate: foraminiferal and isotopic evidence from Sulafjord, western Norway. *The Holocene 11*, 437–446.

Mook, W. G. & Streurman, H. J. 1983: Physical and chemical aspects of radiocarbon dating. *In* Mook, W. G. & Waterbolk, H. T. (eds.): *^{14}C and Archaeology, Proceedings of the First International Symposium (PACT 8), Strasbourg*, 31–55.

Møller, J. J. 1986: Holocene transgression maximum about 6000 years BP, at Ramså, Vesterålen, north Norway. *Norwegian Journal of Geography 40*, 77–84.

Nilssen, E. & Vorren, K.-D. 1991: Peat humification and climate history. *Norwegian Journal of Geology 71*, 215–217.

Nilsson, T. 1961: *Kvartärpaleontologi*. 231 pp. University of Lund, Lund.

Nyholm, E. 1956–69: *Illustrated Moss Flora of Fennoscania. II. Musci.* 799 pp. Natural Science Research Council, Stockholm.

Økland, R. H. 1989: A phytoecological study of the mire Northern Kisselbergmosen, SE Norway. I. Introduction, flora, vegetation and ecological conditions. *Sommerfeltia 8*, 1–172.

Økland, R. H. 1990: A phytoecological study of the mire Northern Kisselbergmosen, SE Norway. III. Diversity and habitat niche relationships. *Nordic Journal of Botany 10*, 191–220.

Osvald, H. 1925: Zur Vegetation der ozeanischen Hochmoore in Norwegen. *Svenska Växtsociologiska Sällskapets Handlingar 7*, 1–106.

Pilcher, J., Bradley, R. S., Francus, P. & Anderson, L. 2005: A Holocene tephra record from the Lofoten Islands, Arctic Norway. *Boreas 34*, 136–156.

Pilcher, J. R., Hall, V. A. & McCormack, F. G. 1995: Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *The Holocene 5*, 103–110.

Pilcher, J. R., Hall, V. A. & McCormack, F. G. 1996: An outline tephrochronology for the Holocene of the north of Ireland. *Journal of Quaternary Science 11*, 485–494.

Plunkett, G. 2006: Tephra-linked peat humification records from Irish ombrotrophic bogs question nature of solar forcing at 850 cal. yr BC. *Journal of Quaternary Science 21*, 9–16.

von Post, L. & Granlund, E. 1926: Södra Sveriges torvtillgånger. *Sveriges Geologiska Undersökningar C 335*, 1–127.

Pouchou, J. & Pichoir, F. 1991: Quantitative analysis of homogeneous or stratified microvolumes applying the model 'PAP'. *In* Heinrich, K. F. J. & Newbury, D. E. (eds.): *Electron Probe Quantitative Analysis*, 31–75. Plenum Press, New York, NY.

Rahmstorf, S. 2002: Ocean circulation and climate during the past 120,000 years. *Nature 419*, 207–214.

Reimer, P. J., Baillie, M. G. L, Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J. & Weyhenmeyer, C. E. 2004: IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon 46*, 1029–1058.

Seppä, H., Nyman, M., Korhola, A. & Weckström, J. 2002: Changes of treelines and alpine vegetation in relation to post-glacial climate dynamics in northern Fennoscandia based on pollen and chironomid records. *Journal of Quaternary Science 17*, 287–301.

Sjörs, H. 1948: Myrvegetationen i Bergslagen. *Acta Phytogeographica Suecica 21*, 1–299.

Slubowska, M. A., Koc, N., Rasmussen, T. L., Klitgaard-Kristensen, D. & Hald, M. 2006: Time-slice recontructions of ocean circulation changes at the continental margins of the Nordic and Barents seas during the last 16000 cal yr BP.; pp. 119–164 in Slubowska, M. A. 2006: Last deglaciation and Holocene reconstruction of Atlantic water flow variability to the Nordic and Barents Seas with a special emphasis on the Svalbard continental margin. Dr. thesis. University of Tromsø. Institute of Geology. UNIS, Svalbard, Norwegian Polar Institute, Tromsø.

Stothers, R. B. 1996: The great dry fog of 1783. *Climatic Change 32*, 79–89.

Thorarinssonn, S. 1967: The eruptions of Hekla in historical times. Societas Scientiarum Islandica. *1*, 1–183.

Tolonen, K. 1966: Stratigraphical and rhizopod analyses of an old raised bog, Varrassuo, in Hollola, South-Finland. *Annales Botanici Fennici 3*, 146–166.

Tolonen, K., Warner, B. G. & Vasander, H. 1992: Ecology of Testaceans (Protozoa: Rhizopoda) in mires in southern Finland. I. Autecology. *Archiv für Protistenkunde 142*, 119–138.

Vorren, K.-D. 2001: Development of bogs in a coast–inland transect in northern Norway. *Acta Palaeobotanica 41*, 43–67.

Vorren, K.-D. & Alm, T. 1985: An attempt at synthesizing the Holocene biostratigraphy of 'type area' in northern Norway by means of recommended methods for zonation and comparison of bio-stratigraphical data. *Ecologia Mediterranea 11*, 53–64.

Vorren, K.-D. & Moe, D. 1986: The early Holocene climate and sea level changes in Lofoten and Vesterålen, North Norway. *Norsk Geologisk Tidsskrift 66*, 135–143.

Vorren, K.-D., Eurola, S. & Tveraabak, U. 1999: The lowland terrestrial mire vegetation about 69°N lat. in northern Norway. *Tromura, naturvitenskap 84*, 1–105.

Wastegård, S., Hall, V. A., Hannon, G. E., van den Bogaard, C., Pilcher, J. R., Sigurgeirsson, M. Á. & Hermanns-Audardóttir, M.

2003: Rhyolitic tephra horizons in northwestern Europe and Iceland from the AD 700s–800s: a potential alternative for dating first human impact. *The Holocene 13*, 277–283.

Wells, C., Huckerby, E. & Hall, V. 1997: Mid- and late-Holocene vegetation history and tephra studies at Fenton Cottage, Lancashire, U.K. *Vegetation History and Archaeobotany 6*, 153–166.

Witham, C. S. & Oppenheimer, C. 2004: Mortality in England during the 1783–84 Laki Craters eruption. *Bulletin of Volcanology 67*, 15–26.

Wohlfarth, B., Blaauw, M., Davies, S. M., Andersson, M., Wastegård, S., Hormes, A. & Possnert, G. 2006: Constraining the age of Lateglacial and early Holocene pollen zones and tephra horizons in southern Sweden with Bayesian probability methods. *Journal of Quaternary Science 21*, 321–334.

Yeloff, D. & Mauquoy, D. 2006: The influence of vegetation composition on peat humification: implications for palaeoclimatic studies. *Boreas 35*, 662–673.

Zielinski, G. A. 2000: Use of paleo-records in determining variability within the volcanism–climate system. *Quaternary Science Reviews 19*, 417–438.

Zillén, L. M., Wastegård, S. & Snowball, I. F. 2002: Calendar years of three mid-Holocene tephra layers identified in varved lake sediments in west central Sweden. *Quaternary Science Reviews 21*, 1583–1591.